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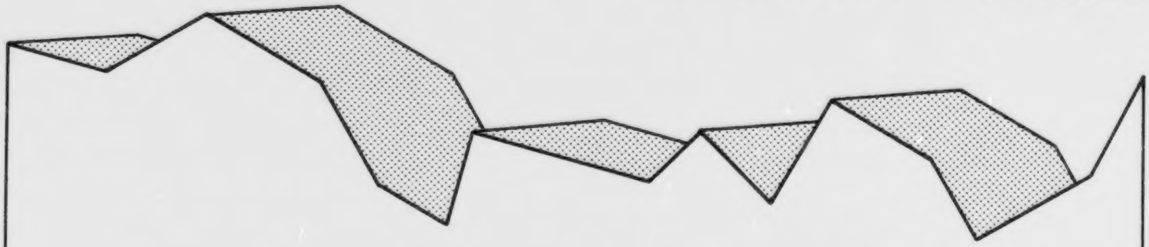

# Ice Control for Arctic Ports and Harbours

## Volume 1

## Final Report

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17. Abstract

This report examines the types of ice problems that may occur in harbours that are operated in ice conditions and presents a description of a range of ice control techniques that could be used in conjunction with certain design approaches to mitigate these problems. Criteria for harbour design are addressed and a number of Arctic and non-Arctic locations are briefly described in order to illustrate the ice problems that are, or may be, experienced. Ice control techniques are evaluated for general application and a case study is conducted of the potential ice problems at Nanisivik, Baffin Island, to illustrate a procedure that could be followed in evaluating ice control techniques for a particular location. Recommendations for data collection to provide necessary design information are also made.

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17 Résumé

Ce rapport récapitule les différents types de problèmes que peut présenter l'accumulation des glaces dans les ports et décrit la gamme des techniques de lutte contre les glaces utilisables concurremment à une approche modifiée de la conception des ports. Il aborde les critères de conception portuaire, puis décrit un certain nombre de sites arctiques et autres, mettant en évidence les problèmes que les glaces peuvent y poser. Il fait une évaluation générale des techniques proposées et prend le port de Nanisivik dans l'île de Baffin comme cas d'espèce pour illustrer la procédure applicable en vue de choisir les techniques à mettre à oeuvre dans un cas particulier. Enfin, il fait des recommandations concernant la saisie des données nécessaires à l'étude proprement dite des techniques à utiliser.

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# 1. INTRODUCTION

As Arctic developments assume an increasingly important role in Canada and year-round navigation becomes a reality, the requirement for rational design of Arctic ports and harbours will become more demanding. The restraints imposed by ice conditions during winter operations will dictate more stringent design considerations than have been necessary to date for seasonal operations. An appreciation of the problems that winter ice conditions can present in harbours and the means of mitigating such problems will assist in the achievement of appropriate designs for Arctic locations. In so doing, knowledge gained from operation in ice in more temperate climates such as the Great Lakes and Eastern Canada and in areas outside this country will form a valuable input to the design process.

In this report, the ice problems that could be experienced in harbours during winter operations are generalized into three categories, and a number of present and possible future harbours are discussed in terms of these problems. Depending on the location of the harbour and the ice regime, the problems experienced could be due to one or all of the following.

-The accelerated buildup of ice in the berthing area from repeated passages of vessels due to the freezing of water that is repeatedly exposed to the atmosphere.

-The accelerated buildup of ice on the dock structure due to tidal action.

-The interaction of the dock and/or vessels with ice driven by environmental forces.

Each of these problems is discussed in Section 2 of this report, and on the basis of these problems, criteria are presented for the siting, layout, design and operation of arctic ports and harbours.

A range of ice control techniques that might be employed to mitigate these problems is discussed and, for each technique, a general engineering description is presented. These techniques, which have been identified from an extensive literature search and contact with port and harbour authorities, are broken into four broad categories. These categories are

-ice suppression, which inhibits the formation of ice

-ice breaking, which involves the breaking, cutting, or destruction of ice

-ice removal, which involves the physical displacement of ice by lifting, submerging, pushing or piping

-ice diversion, which is the deflection or arrest of moving ice to prevent collision with dock or vessel.

These techniques are discussed in detail in Sections 3 to 6 and an evaluation of each is presented in Section 7.

As an example of the application of the evaluation techniques, the port of Nanisivik, Baffin Island, is examined in a case study. The most promising techniques for ice control in that port are reviewed in detail and a number of novel control methods are presented.

Finally, recommendations for data gathering and information improvement are presented.

# 2. ICE CONTROL PROBLEMS AND HARBOUR DESIGN CRITERIA

Each of the ice control problems presented in Section 1 is discussed in detail in this section. From a consideration of the ice control problems, a number of criteria are established for the siting, layout, design and operation of ports and harbours. In addition, examples of Canadian ports and harbours are presented, and the types of ice problems that are or may be experienced in these locations are briefly mentioned.

## 2.1 Ice Control Problems

### 2.1.1 Ice Buildup in the Ship Track

The passage of vessels along the same track in a continuous ice sheet results in an accelerated formation of ice through the repeated exposure of water to the atmosphere. After a certain number of passages, the accumulation of ice may reach the point where further passages will be precluded. At this time, the track may have to be abandoned in favour of an alternative route. The same ice buildup will occur in the docking area and, if the ice accumulation proves to be excessive, ice control techniques will be required to permit proper berthing of vessels.

Two mathematical models or algorithms for this ice buildup have been published, and each of these is described below.

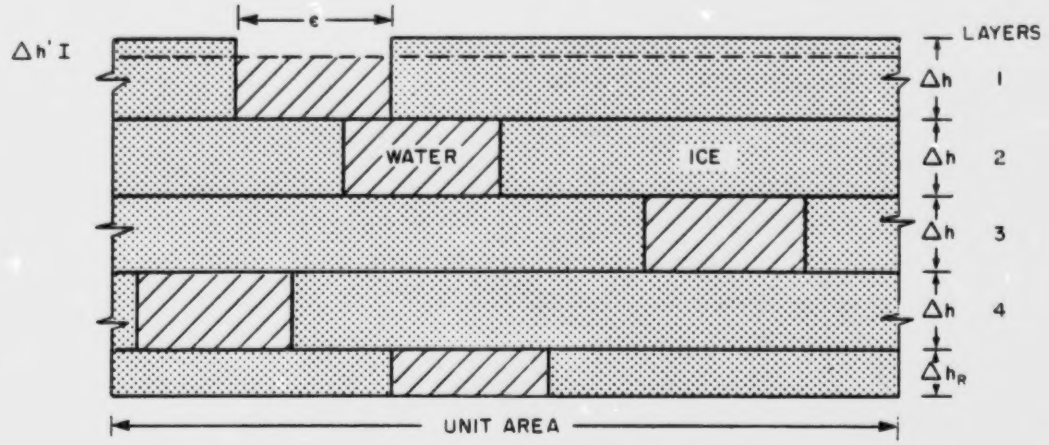
#### 2.1.1.1 Michel's Algorithm for Ice Growth

After observing the modes of accumulation of broken ice and ice growth in ship tracks, Michel (1975) proposed the simple physical model shown in Figure 2-1. It is made up of a matrix of superimposed ice pieces of porosity $\varepsilon$ and of basic thickness $\Delta h$ with a residual ice thickness ($\Delta h_r$) at the bottom. A typical track profile is also shown in Figure 2-1.

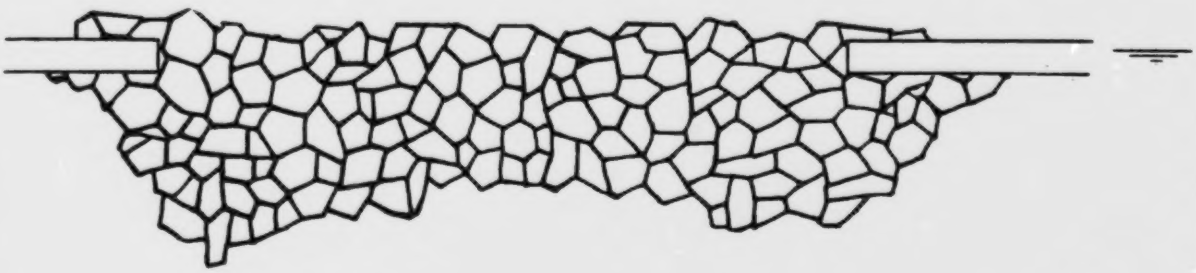
The equations below present the overall increase in ice thickness ($\Delta h_T$) between ship passages. (Some of the symbols and formulations have been changed slightly from the reference in order to clarify the presentation.)

The additional ice produced in the surface layer is written as

$$\Delta_1 = \frac{\varepsilon}{1-\varepsilon} (\Delta h - \Delta h^1) + \xi \sqrt{\alpha^2 \quad \Delta D} - (\Delta h - \Delta h^1).$$


ε
Δh'I
LAYERS
Δh 1
WATER
ICE
Δh 2
Δh 3
Δh 4
Δh_R
UNIT AREA

MICHEL'S MODEL OF ICE GROWTH IN SHIP'S TRACK
(MICHEL, 1975)



TYPICAL PROFILE IN SHIP'S TRACK AFTER REPEATED PASSAGES

FIG. 2-1

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS
MICHEL'S MODEL AND TYPICAL TRACK PROFILE

ACRES

The layers of ice inside the matrix contribute growth

$$\Delta_2 = \varepsilon \sum_{i=2}^{k} [\sqrt{\{(i-1)\Delta h\}^2 + \alpha^2 \Delta D} - (i-1)\,\Delta h].$$

and the increase in residual ice formed at the bottom is

$$\Delta_3 = \nu(1-\varepsilon)^{n-1}[\sqrt{(n\Delta h + h_r)^2 + \alpha^2 \Delta D} - (n\Delta h + h_r)]$$

The total increase in ice thickness is then

$$\Delta h_T = \Delta_1 + \Delta_2 + \Delta_3$$

where

$k$ = the critical number of layers required to stop the formation of residual ice

= highest integer $\leq 1/(1-\varepsilon)\varepsilon$

$\xi$ = 1 for $\sqrt{\alpha^2}\ \Delta D \leq (\Delta h - \Delta h1)$

$\xi$ = $\varepsilon$ for $\sqrt{\alpha^2}\ \Delta D > (\Delta h - \Delta h1)$

$\nu$ = 1 for $n \leq K$

= 0 for $n > K$

$\Delta h^1$ = distance between the top of the ice and the water surface

$\Delta h$ = thickness of ice layer i, as calculated from $\alpha\sqrt{\Delta D}$

$\alpha$ = local heat exchange coefficient

$\Delta D$ = number of degree-days of frost between successive ship passages.

Comparisons of the model predictions with field data have been made from observations in Lulea Harbour in the Gulf of Bothnia (Sandkvist, 1981). The profiles of ice in the ship tracks were measured by drilling, sonar and diver observations. The maximum thickness of ice was 5 m at the edge of the track while the average thickness across the track was about 2 m. The natural ice thickness was a maximum of 0.8 m. The Michel algorithm was used to simulate the ice growth, and the authors report that the computed ice thickness corresponded reasonably well to the average ice thickness measured in the actual ship track (Figure 2-2).

#### 2.1.1.2 Ashton's Algorithm for Ice Growth

The algorithm suggested by Ashton (1974) is based on a somewhat different approach to ice growth in a ship's track. According to his observations, several passages of a vessel result in a more or less uniform coverage of the channel area. The percentage of open water surface area is in the order of 20 - 30 percent. As a result of this open water area, the production of ice tends to increase.

On each day of traffic, it is assumed that a fraction ($\varepsilon$) of open area is exposed in the channel and this fraction freezes and thickens as an initial ice cover. The other fraction ($1-\varepsilon$) continues to thicken, but the effective initial thickness at the start of the freezing interval is assumed to be $h_{i-1}/(1-\varepsilon)$ to account for the fact that the broken ice is contained in the channel track and, hence, presents an effective thickness greater than before. Thus, the average thickness is given by

$$h_i = (1-\varepsilon)\ [(\frac{h_{i-1}}{1-\varepsilon})^2 + \alpha^2\ \Delta D^{0.5} + \varepsilon\alpha\Delta D]^{0.5}$$

where

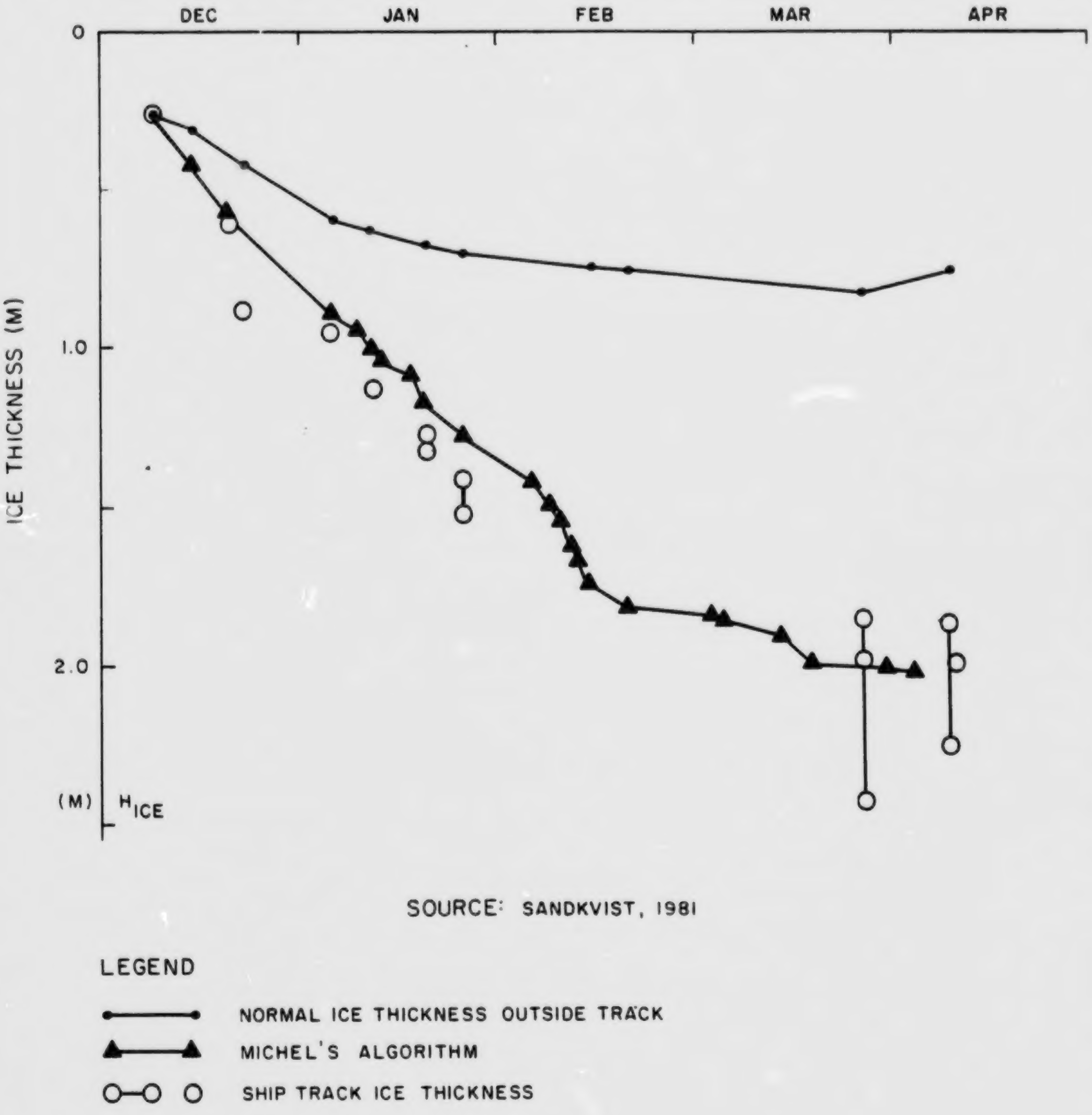
$h_i$ = the average thickness at the end of the period of ice growth

$h_{i-1}$ = the effective thickness at the beginning of the period.

Computer programs were developed for both Michel's and Ashton's algorithms and these were used to generate example accelerated ice buildup curves based on an assumed number of freezing degree-days and vessel frequency. The results are shown in Figure 2-3. The normal undisturbed ice growth is also shown for comparison purposes.

### 2.1.2 Ice Buildup Due to Tidal Action

In tidal harbours, dock support structures can accumulate exaggerated ice growth due to the freezing of water on vertical surfaces following a high tide. Such a growth creates a buildup of ice that may be sufficient to hamper ship berthing. In addition, this ice accumulation must be



SOURCE: SANDKVIST, 1981

FIG. 2-2

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ICE THICKESS IN SHIP TRACK IN LULEA HARBOUR

ACRES

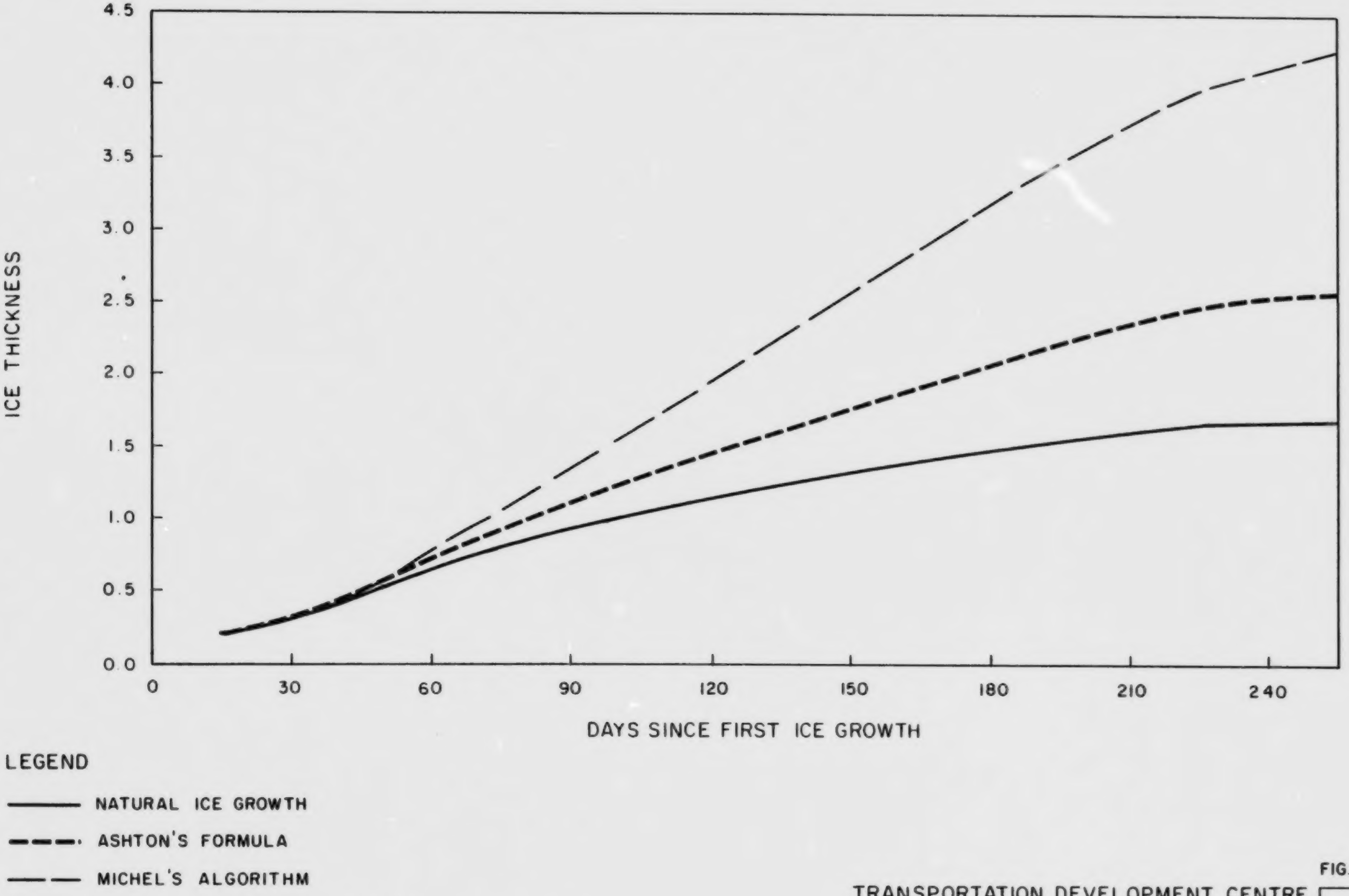


FIG. 2-3

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

EXAMPLE OF THEORETICAL
ICE GROWTH IN A SHIP TRACK WITH REPEATED PASSAGES FOR A TRIP ONCE EVERY 15 DAYS

considered during design to ensure that the dock and the foundation can accommodate the added loads.

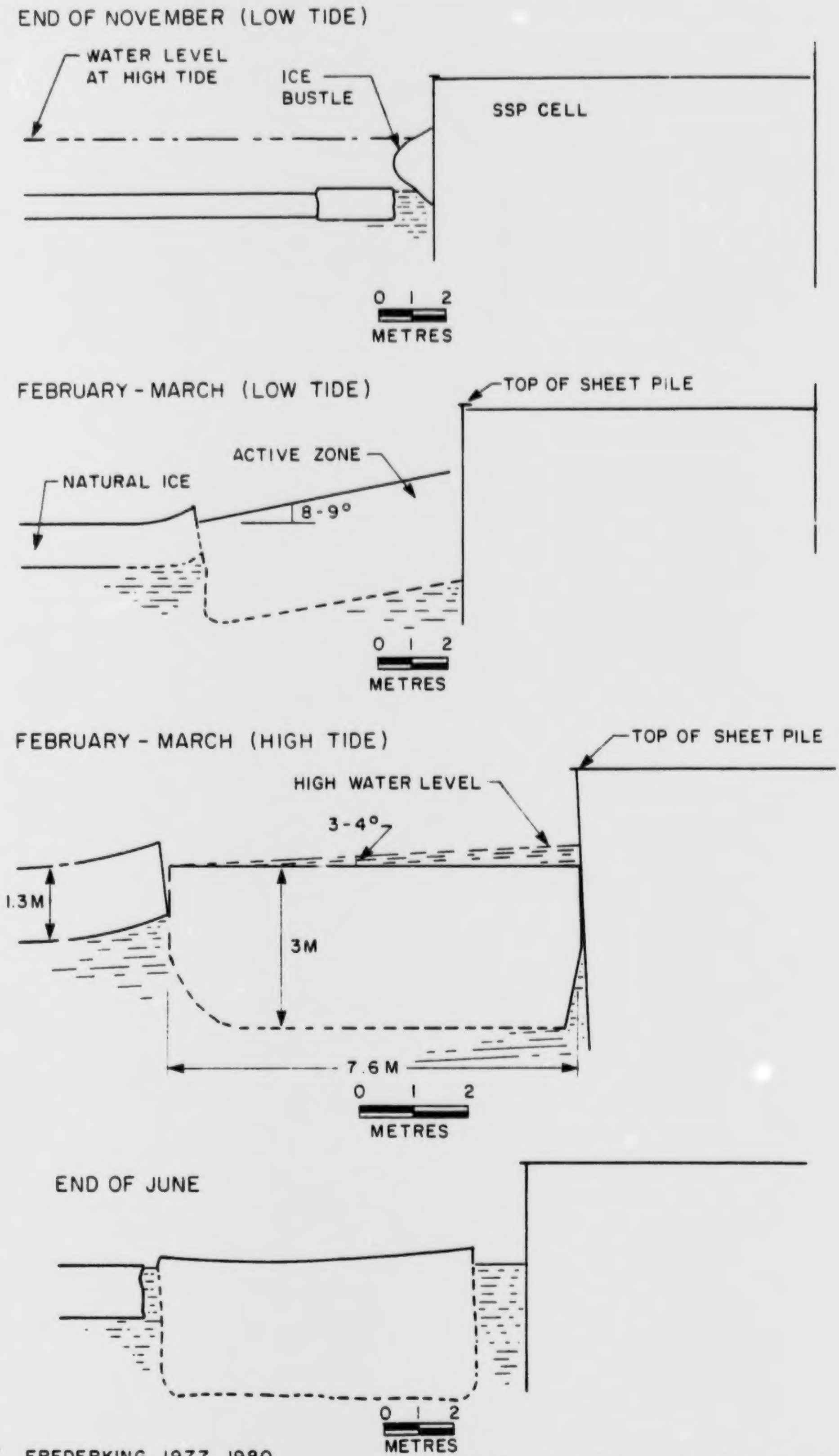
The initial layer of ice on the piles or columns forms during falling tide when a film of water is left on the pile. This layer gradually becomes built up with each tidal cycle and forms an ice "bustle". Depending on the dock structure, these "bustles" may eventually join and form a lattice of ice ribs between the piles or they may become incorporated into the larger ice sheet as it grows adjacent to the dock. The exact process depends on the dock configuration and the tidal extent. Growth rates of these ice cylinders or bustles have been measured at greater than 2.5 cm/d. At the port of Anchorage, Alaska, where the tidal range extreme is 12.8 m and the pile spacing is 3 m, it has been estimated that the ice accumulation on the support piles nearly doubles the load requirement of each pile and ultimately the bearing foundation (Perdichizzi and Yasuda, 1978). Buoyancy uplift forces at high tide are minimized because the tides prevent the formation of large thick unbroken ice sheets.

In some cases, the tides cause the ice formed at the dock to effectively form an active zone which responds to the tides and acts as a hinge between the outer, larger ice sheet and the dock structure. For very low vessel frequencies, this active zone may build outward to a distance of several metres from the dock as well as increase in thickness to several times the regular ice thickness due to repeated floodings. This ice growth at the dock may severely hamper docking.

Probably the best documented case of such increased ice accumulation due to tidal action is a description of ice action at the Nanisivik dock, Strathcona Sound, by Frederking (1977, 1980). Figure 2-4 shows the sequence of ice growth and action which could lead to difficult ice conditions at the dock. (A detailed discussion of the Nanisivik dock and associated ice control problems is presented in Section 8.)

### 2.1.3 Interaction of Moving Ice With Dock or Vessels

Strictly speaking, the possibility of loads being exerted on the dock structure by moving ice during breakup and freeze-up should be accommodated in the design of the structure. However, in some cases, particularly from an operational point of view, it might be desirable to prevent the moving ice from impacting the dock or entering the berthing area where it could interfere with vessel berthing. In these cases, it is necessary to contain or divert the ice floes, and the ice control techniques required to do this will be likely different from those required to prevent or mitigate the other problems discussed above. Such control techniques will be required to restrain the ice or create a sufficient counter-current to move the ice away from the



END OF NOVEMBER (LOW TIDE)

WATER LEVEL AT HIGH TIDE
ICE BUSTLE
SSP CELL
0 1 2
METRES

FEBRUARY - MARCH (LOW TIDE)

TOP OF SHEET PILE
ACTIVE ZONE
NATURAL ICE
8-9°
0 1 2
METRES

FEBRUARY - MARCH (HIGH TIDE)

TOP OF SHEET PILE
HIGH WATER LEVEL
3-4°
1.3M
3M
7.6 M
0 1 2
METRES

END OF JUNE

0 1 2
METRES

SOURCE FREDERKING 1977, 1980

FIG. 2-4

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ICE CONDITIONS THROUGHOUT WINTER AT NANISIVIK DOCK control zone. The ability of any techniques to accomplish this will depend on the environmental forces driving the ice floes and on their resultant energy.

The environmental driving force can be determined from the standard drag force equation which may be written as

$$F = C_D \rho A v^2$$

where

$F$ = driving or drag force
$C_D$ = drag coefficient
$\rho$ = density of driving wind or water
$A$ = surface area of ice
$v$ = speed of wind or water.

Movements of landfast ice could also occur during winter in harbours that are exposed to long expanses of ice in the direction of the prevailing winds. Stresses developed in the ice cover could result in large ice movements and pileups of ice at the dock if weak zones exist in the harbour ice. Such possibilities should, in the first instance, be prevented by suitable siting of the dock; otherwise, a protective structure may be required to arrest the moving ice.

## 2.2 Harbour Design Criteria

It is evident from the discussion of ice problems that consideration should be given to a number of ice effects when locating ports and harbours, and when designing dock structures for these locations. Such considerations are in addition to the typical conditions one considers for open water harbour and dock design, such as winds, waves, tides, currents and bottom conditions. Design for ice conditions, particularly in an arctic environment, will complicate the consideration of these factors. Arctic design will also take into account the effect of low temperatures on material performance and the influence of permafrost on foundation design; however, these factors are not considered in the present discussion, since this is confined to design considerations associated with ice problems only. These considerations are discussed in the following sections under four headings; these are location, layout, design and operation.

### 2.2.1 Location

Typically, the approximate location or siting of a harbour is determined by the location of an industrial demand or settlement. In considering the effects of ice on harbour siting, it is clear that maximum protection from moving ice is desirable, while at the same time, maximum accessibility to the harbour must be provided. Protection is best provided by locating the harbour in land-fast ice and with the entrance to the harbour oriented away from the direction of the prevailing wind. This will also encourage ice floes to move out of the harbour during summer.

If the harbour is exposed to moving pack ice, particularly multiyear ice, the ice loads on the dock would be more severe and vessels operations could be significantly hindered. Where harbours must be located in moving ice, as for example, in the case of offshore loading terminals, provision should be made in the design to minimize ice interaction with the dock structure and interference with vessel operations.

Accessibility to the harbour will be determined by ice conditions outside the harbour. If large areas of high concentration multiyear ice exist outside the harbour, accessibility will be more difficult than if only first-year fast or pack ice exists. Likewise, the occurrence of ridges will hinder access to the harbour.

Because of the ice problems that can result from tidal effects, the harbour should be located where possible in an area of low tidal range. Otherwise, considerable amounts of ice could accumulate on the dock structure which could lead to berthing problems as well as result in increased loads on the dock structure and the foundation. This problem would be manifested more in a seasonal rather than a year-round operation.

Where possible, the harbour should be located in an area which has a natural source of ice control. This could be in an area which shows a thermal stratification in the water column with warmer water at depth, or is near a freshwater lake whose bottom water could be transported to the harbour and used as a means of ice control. If the harbour is to serve an industrial complex, it should be located as close as possible to the plant to utilize any waste heat that may be available from the plant.

### 2.2.2 Layout

The siting and layout of harbour components should be carried out so that the ice problems are minimized. The dock orientation should be such that movement of the ice cover under the influence of the wind would result in minimum loads on the dock and minimum interference with harbour operations. The layout would be particularly important in a river port where moving ice could have serious effects on dock operations if the dock orientation is such that the ice is blocked during its downstream movement.

The layout is also important from the point of view of vessel manoeuvering in ice, particularly if large vessels such as very large crude carriers (VLCC's) or LNG carriers are being considered. If the vessel is to make a turning circle in the harbour, a considerable area will be required. This area will depend on the vessel design and the degree of tug assistance provided. Without tug assistance, it has been estimated that the turning diameter of a 300 000-tonne vessel in arctic ice is approximately 12 km (Griesbach and Kremer, 1973). The turning diameter of the LNG carrier designed for the Arctic Pilot Project is estimated to be 4 km. In such cases, the dock and other harbour facilities should be sited so as to allow the maximum area for vessel manoeuvering.

### 2.2.3 Design

Strictly speaking, harbour design refers to all four factors being presently discussed; however, in this section, design is primarily concerned with the dock structure and, in particular, to a consideration of the ice effects on dock design. While basic inputs to the design of any dock will be the intended use of the dock and the characteristics of the associated vessels, docks designed for operations in ice should exhibit features which minimize resistance to the berthing vessel and ice forces on the structure, and which mitigate ice problems in the berthing area. One means of accomplishing this would be an open-face design which allows ice to be pushed under the dock by the berthing vessel.

In general, the ice loads that may be exerted on the dock come from three sources; these are,

(i) wind and current driven ice either in the form of individual floes or large sections of the ice cover

(ii) small ice pieces jammed between the vessel and dock during berthing manoeuvers

(iii) ice buildup on vertical surfaces due to tidal effects which increase foundation loads and may cause horizontal and vertical loads due to hinging at these surfaces. In earthquake zones, the "added mass" of this ice would have to be considered in the design process to evaluate the effect on the structure response to earthquake loading.

Extra bearing loads resulting from (iii) may be easily obtained once the ice accumulation resulting from tidal effects is determined; the effect on bearing surfaces may then be estimated. The loads resulting from the hinging effect described in Section 2.1.2 have not been well quantified to date; however, for substantial dock support structures, it is unlikely that these forces would govern design. The most favourable design would, of course, eliminate such loadings by preventing ice from accumulating on and around the dock structure. Such designs would incorporate ice control techniques to achieve this.

In determining the ice forces exerted on dock structures, the traditional approach has been to calculate the so-called effective pressure on the dock member due to crushing from a consideration of the interaction between the ice and the member. In obtaining forces due to crushing, the formula proposed by Korzhavin (1962) has been used extensively. This formula expresses the effective ice pressure in terms of the crushing strength and a number of coefficients which depend on the shape of the member, the degree of contact and the rate of movement (or strain rate) of the ice. The resulting force per unit width of the member is then given by

$$F = p_{eff}h = \sigma_c kmIh$$

where

$p_{eff}$ = effective pressure
$h$ = ice thickness
$\sigma_c$ = crushing strength of the ice which depends on brine volume and strain rate
$k$ = contact coefficient = 1 for perfect contact
$m$ = shape factor = 0.9 for circular members
$I$ = indentation coefficient which tends to 1 for wide members and 2.5 for narrow structures (when member width/ice thickness is equal to 1).

The use of this formula will result in the largest force per unit width of structure when cold, low salinity ice interacts with a narrow member. With very wide structures, the effective ice pressure will be lower because of the variation in local contact and nonsimultaneous failure across the structure. Thus, while local stresses over any one small area of a wide structure could be high, the average crushing stress across the total structure width would be low.

Forces on dock support members could be reduced if the ice failed in bending rather than crushing since the bending strength of ice is only a fraction--possibly as little as 1/10--of the crushing strength. The dock members could thus be configured to induce bending in the ice as it contacts the dock.

For offshore terminal areas, such as those envisaged by the petroleum industry, designs may be based on the artificial island concept. For such very large structures exposed to ice movement over large distances, the governing ice forces may be due to winds and currents. The design loads calculated from the traditional ice/structure interaction approach described above would lead to very high values of forces because of the very thick rubble field that normally builds around such structures. Recent information indicates that the available driving force in the ice cover further removed from the structure is significantly lower than this. In other words, the ice itself will fail under lower forces than those calculated for the ice/structure interface, and as a result, the structure can be designed for these lower forces. These considerations would also apply in some cases to an artificial structure which is used to protect a conventional harbour from ice movement.

### 2.2.4 Operation

From an operational point of view, minimizing the ice problems in harbours would expedite the normal procedures relating to ship and plant. The intended operation of the harbour is obviously a basic input to the overall harbour and dock design, and in that sense, allowances would be designed into the system to mitigate ice interference with harbour and vessel operations. The degree of tolerance of ice interference will depend to some extent on the use of the harbour. As an example, if a vessel needs to berth immediately adjacent to the dock for loading and unloading, it would be essential not to have ice jammed between vessel and dock. On the other hand, if the vessel uses loading arms, it might be able to tolerate some ice in that area, and the ice control requirements might be lessened.

The degree of the ice problem will also depend on whether the operation is supported by a dedicated icebreaking tug in the harbour. If a tug were available to aid in berthing, the ice problems facing the berthing vessel would probably be reduced. On the other hand, consideration would have to be given to the effect of the extra volumes of ice generated.

## 2.3 Description of Selected Ports and Harbours

From discussions with personnel from the Transportation Development Centre, a list of ports and harbours was prepared for consideration in the study. Data on these locations were then obtained from a number of information sources, and basic descriptions of the physical characteristics of the locations were derived. These characteristics pertain to the physical environment and dock features. A detailed listing of all available data on the selected sites is included in Appendix B. Few of these sites are used during winter so that the ice problems presented are largely based on experiences elsewhere, on the environmental characteristics of the harbour, and the physical features of existing dock structures.

The following Arctic sites were considered

-Bridport Inlet
-Cambridge Bay
-Frobisher Bay
-McKinley Bay
-Nanisivik

-Polaris Bay
-Rea Point
-Resolute Bay
-Sachs Harbour
-Tuktoyaktuk.

While the emphasis in this study is placed on Arctic locations, additional sites outside the Arctic were also considered since ice control problems experienced there could provide valuable input to design for Arctic locations. Three sub-Arctic and temperate locations were considered as being representative of more southern conditions. These are Churchill, Manitoba; Northwest Point in Lake Melville, Labrador; and Thunder Bay, Ontario.

A brief description of each of the sites, together with experienced or anticipated ice problems, is given below.

### Bridport Inlet

Bridport Inlet, on the south coast of Melville Island, is the planned location for the Arctic Pilot Project's LNG Terminal. It is a semicircular shaped inlet, facing south, with an area of 93 km$^2$. The ice in the inlet is fast with freeze-up occuring in mid- to late September and breakup in late July or early August. The maximum ice thickness in an average year is 2.2 m. Water column temperature measurements indicate a constant temperature throughout at -1.8°C with a salinity of 32.3 parts per thousand. The maximum tidal range is estimated to be 2.1 m with the mean range being 0.9 m. Surface currents are in the order of 5 cm/s. Average wind velocity is 5 m/s and the prevailing direction is northwest. The dock location is planned for the northeast side of the inlet to allow sufficient manoeuvering room for the LNG carriers. The primary ice control problem will be due to the accelerated buildup of ice at the dock face due to the passage of the carriers. It has been estimated that, on the basis of 1 vessel every 15 days, the ice in the track will build up to an average thickness of 6 m by the end of winter (Acres, 1978). It is thus considered essential to control this ice growth.

### Cambridge Bay

Cambridge Bay is located on the south shore of Victoria Island and is an Arctic administration, transportation and supply centre. Ice starts forming in the bay in late September with complete coverage of fast ice by mid-October. Breakup usually starts in mid-June and the bay is free of ice by the third week in July, although an ice barrier often persists at the outer entrance of the bay. The maximum ice thickness in an average year is estimated from freezing degree-day records to be 2.1 m. The predominant wind is northwest and the mean tide range is 0.4 m. Temperature and salinity profiles made in 1961, in conjunction with a bubbler installation, show almost constant temperature and salinity conditions to a depth of 30 m with slight increases below this (Ince, 1963). The minimum water depth at the dock is 4.9 m.

### Frobisher Bay

Frobisher Bay is located at the south end of Baffin Island, and the village of Frobisher is at the head of the bay in Koojesse Inlet, over 200 km from the mouth of the bay. Koojesse Inlet usually freezes in the second or third week in October but freeze-up may not be complete until mid-November. Breakup usually starts at the end of June and the harbour is generally ice-free by July 25 although, in some years, ice remains well into August, and small amounts of drift ice may be encountered throughout summer. No dock exists in Koojesse Inlet and ships supplying Frobisher are required to anchor offshore. Wind directions are prevailing northwesterly throughout the year although, in summer, precautions are required against southeasterly winds which have open-water fetch through the bay.

If a dock of conventional design did exist at the head of Frobisher Bay, it would very likely experience ice problems due to the very large tides in the bay which would cause considerable ice accumulation on the dock structure. Average tides in Koojesse Inlet are 7.8 m, with large tides being over 11 m. Normal ice growth would be in the order of 1.6 m but, at the dock, thicknesses of several times this value could be experienced over a winter due to the tidal effects.

### McKinley Bay

McKinley Bay, located on the east side of MacKenzie Bay, is used by Dome Petroleum Limited as a winter harbour for its drilling fleet. Dome Petroleum Limited has dredged a channel and built an artificial island to protect the basin from ice movement which could result from the site's exposure to winds from the west and the northwest. (Such a movement occurred in December 1979.) Air temperatures, ice growth and tidal ranges in McKinley Bay are probably similar to those at Tuktoyaktuk which is to the southwest. Uniform ice growth is estimated to reach a maximum of 1.7 m in an average year. Freeze-up occurs in late September and breakup in mid-June. At the present time, the facilities do not include a standard dock; there is, however, a dry dock facility which is used for ship repairs over the winter. The icebreaker, M.V. Kigoriak, and supply ships are used to maintain a broken ice cover in the basin. There is some evidence of temperature stratification, probably due to the MacKenzie River, so that movements of this bottom water might be effective in ice control.

## Nanisivik

Nanisivik is located on the south shore of Strathcona Sound, Baffin Island, and is the site of a lead and zinc mining operation which commenced production in 1977. The concentrate is stockpiled over the winter and is shipped out during the period July through October, which corresponds with the breakup and freeze-up of Strathcona Sound. The maximum ice thickness in an average winter is approximately 1.6 m; however, ice buildup at the dock due to tidal effects results in considerably greater thicknesses in the berthing area. It is this ice growth that would prevent ships from berthing close to the dock. The mean tide range is 1.5 m with the large range being 2.5 m.

No data are available on the hydrographic structure of the water column; however, it is anticipated that the temperature and salinity are constant throughout. Wind data based on data for Arctic Bay, 30 km to the southwest, indicate that prevailing winds are from the northwest for most of the year. Precipitation is light at Nanisivik with an annual total of 12.6 cm, 40 percent of which falls as rain during the summer season. (Nanisivik is discussed in more detail in Section 8.)

## Little Cornwallis Island

Little Cornwallis Island is the site of Cominco Limited's Polaris project which is a lead and zinc mining development. Very little information is available on the environmental conditions at this site; however, it is expected that conditions are similar to those at Resolute Bay on Little Cornwallis Island.

McDougall Sound, to the south of Little Cornwallis Island, is covered with first-year ice from November to July. Fracturing of this ice normally begins during the first week of August with total ice concentration reducing to open pack or less by the last week of the month. New ice usually begins to form during the third week of September with consolidation being complete by late October or early November. Considerable variation in the breakup and freeze-up dates can occur from year to year.

The dock is located on the southwest corner of the island and faces Crozier Strait. It is of steel sheet-pile construction with backfilled interconnecting cells, and is approximately 113 m long and extends 122 m from shore. Ice buildup on the dock face and near the dock can be expected due to tidal effects. It is also possible that in a year-round operation, large-scale movements of the ice cover could result if weak zones exist from vessel traffic. Since the dock is exposed to Crozier Strait, ice pile-ups could occur from such movements. The dock could also be impacted by ice floes during breakup.

### Resolute Bay

Resolute Bay is located on the south coast of Cornwallis Island and is a centre of transportation, communication and administration for the high Arctic. Ice formation begins in mid-September and the last icebreaker normally leaves late in the month under present seasonal operations. The ice then remains fast throughout the winter. Ice breakup is assisted by an icebreaker in early August and, thereafter, the ice conditions in the bay depend on wind conditions. The bay becomes blocked by ice during extended periods of west winds and becomes ice-free in prevailing northeast and east winds. During winter, the prevailing winds are northwest. Maximum ice thickness in an average year is 1.8 m. Tides in the bay have a mean range of 1.8 m. At the present time, no docks exist in Resolute Bay and ships use two gravel jetties. Resolute Lake, which is about 1.5 $km^2$, drains into the bay via Resolute Creek.

### Sachs Harbour

Sachs Harbour is located on the southwest corner of Banks Island and lies at the mouth of the Sachs River. The harbour is exposed to the west which can lead to ice encroachment into the harbour during summer. Freeze-up usually starts around the first of October and the harbour is completely frozen over by the middle of the month. Breakup normally begins in mid-June with the harbour clearing of ice near the middle of July. In a normal year, the ice grows to a thickness of 1.7 m; the record maximum is 2.3 m which was measured in 1961. A submerged sand bar extends across the entrance to the harbour; the depth of the bar changes due to ice action.

It appears that Sachs Harbour could experience ice problems in summer as well as winter if it were used year round. Ice movements are possible in summer when the ice outside the harbour is pushed in by west winds. It is also possible that, given weak zones in the harbour ice cover in winter, sustained west winds on the outside pack could result in ice pileups against harbour structures. At the present time, there are no docks in Sachs Harbour.

### Tuktoyaktuk

According to the "Sailing Directions for Arctic Canada 1981", Tuktoyaktuk harbour is relatively deep and sheltered, and is the best harbour in the southern Beaufort Sea. The harbour is used as a transfer point for freight from the south and as an offshore supply base for the petroleum industry.

Freeze-up in Tuktoyaktuk Harbour occurs between late September and mid-October, and outside the harbour about 1 week later. Breakup usually occurs between June 18 and

June 28, but due to little water movement in the harbour itself, the ice moves out slowly or melts in the harbour. After breaking up, the ice may freeze again temporarily and pressure ridges may develop. The maximum ice thickness in an average year is estimated to be 1.7 m based on a freezing degree-day record of 4,500°C-d.

The mean tidal range in the harbour is 0.3 m. Measurements of the temperature and salinity structure of the harbour water during winter indicate that a slightly warm layer of saline water exists below about 6 m and is overlain by a layer of freshwater from the MacKenzie River. A temperature of up to +0.25°C has been measured at a depth of 8 m (Ince, 1963).

At present, there are four docks in the harbour; three are privately owned and one is a public wharf. Depths alongside vary from 2.1 - 6.1 m.

### Churchill

The Port of Churchill is situated at the mouth of the Churchill River on the west side of Hudson Bay and is mainly a grain terminal port. Freeze-up is usually complete by mid-November and breakup occurs in early June. At the present time, the harbour becomes unnavigable about 22 days in advance of the final freeze-up. The average closing date for navigation is late October. However, because of insurance requirements, most vessels leave the harbour by October 15. Ice conditions in Hudson Strait dictate the closure of navigation by November 10 in an average year so that the season in Churchill could be extended if the peculiar ice conditions in the harbour could be controlled.

The ice problem in the harbour is created by river ice moving past the dock on ebb tide. Because of the harbour configuration and dock location, the ice has to sweep along the dock face. If a ship happens to be at the dock, the ice forms a jam between the ship and the dock face, and can exert large loads on mooring lines. The ice movement also effectively prevents bringing ships into the dock. This problem has not been as severe in recent years due to lower river outflows caused by the diversion of the Churchill River for the Nelson River hydroelectric project in Manitoba. Lower river flows imply smaller amounts of frazil ice. An investigation of ice control techniques was carried out by the National Research Council as a part of a model study of the harbour (Pratte, 1977). Several types of control structures were modelled.

Over the winter, the ice builds to large thicknesses near the dock due to tidal effects. In fact, an ice collar ("bustle") forms at the dock first due to the tide, even when the harbour is navigable. The mean tidal range at Churchill is 3.4 m with the maximum range being about 6 m. The ice thickness based on freezing degree-day records would be 1.6 m; however, due to tidal effects, the thickness near the dock could be considerably higher than this.

Because of this increased growth of ice at the dock face, damage results to the dock and repairs are required each spring. The dock is a wood crib wharf constructed from 30-cm by 30-cm timbers and faced with 10-cm by 30-cm lining planks. The dock is 838 m long.

Temperature and salinity measurements made in the harbour during freeze-up in 1964 and 1965 have been reported by Dick (1967). These measurements, which were recorded mainly at a depth of 3 m, showed that the river water reaches the freezing temperature earlier than the sea water, and the harbour does not become fast until the sea water reaches the freezing point.

### Northwest Point, Lake Melville

Northwest Point, in the western end of Lake Melville, Labrador, is being considered as a site for a year-round harbour to support industry in Labrador. The site is approximately 120 km from the open sea, and the plan would require the transit of this distance of landfast ice by ice-breaking vessels. The Labrador pack ice lies outside this area. Freeze-up at the site starts in early to mid-November although the entire lake may not consolidate until mid- to late December. Breakup occurs in early to mid-June with the western end of the lake breaking up first due to the influence of inflow from Northwest River and Churchill River. Maximum ice thickness in a normal year is approximately 0.85 m. Snow cover can be high in mid- and late winter. In March, it is not uncommon to have 0.50 m of snow covering the ice. The water in the west end of the lake has a low salinity due to river inflow, and there is evidence of a warm water layer at 10 - 15 m during winter. Tidal effects are felt at the west end of the lake although the range is probably less than 0.5 m. During breakup, ice pileups have occurred on nearby shoals during periods of strong winds. Ice problems in this area could thus result from the three general sources discussed previously.

### Thunder Bay

Thunder Bay, at the head of Lake Superior, is the major grain terminal on the St. Lawrence Seaway System. It is presently operational from approximately April 1 to December 31. Investigations are ongoing into ways of ensuring that the start-up date can be guaranteed for any year rather than being subject to the ice conditions experienced in any given winter. The maximum ice thickness in an average year in Thunder Bay is 0.85 m. Winds are predominantly from the west during winter. The ice problem in Thunder Bay is primarily due to the ice growth in the slipways between the grain elevators; this ice prevents ships from convenient access to the docks.

The ice problems that could arise at any of these locations will be largely dependent on the operation of the port. With year-round traffic, the greatest problem in most of the ports will likely be created by the increased buildup of ice in the berthing area due to repeated ship passages. This will be particularly true for ports located in landfast ice. For river ports or those near the mouths of rivers, particularly in southern areas such as the St. Lawrence River, the primary problem is due to moving ice which needs to be deflected away from the berthing area to avoid interference with vessel operations. In nontidal areas such as the Great Lakes, the primary problem created by year-round traffic would certainly be the accelerated buildup of ice due to repeated passages.

In tidal areas, the buildup of ice on dock structures would probably be of greater concern during a seasonal rather than a year-round operation since large ice thicknesses could accumulate near the dock by the end of winter. The lateral extent of this ice buildup would probably depend on the tidal range as described previously since a moderate range would lead to an active zone which would promote flooding and subsequent increased width as well as thickness. In areas of extreme tidal range, as for example Frobisher Bay, the thickness of ice that would accumulate would be too large to allow the development of such an active zone; however, very large loads could be added to the structure due to the weight of this ice. In areas where a tidal active zone would develop during a seasonal operation, the primary ice problem in a year-round operation would probably be due to accelerated buildup from vessel traffic. The relative severity of these two problems would depend, of course, on the frequency of vessel arrivals.

In tidal areas where a continuous fast ice cover does not exist over the winter as in the St. Lawrence River ports, the ice buildup on dock structures could be a problem throughout the winter and in some cases ice control systems have been installed to overcome this problem. These techniques have application to Arctic locations as well since the problem is similar.

In some areas, consideration would have to be given to the problems that could arise from large-scale ice movements. This would be of greater concern during a year-round operation because of weak zones introduced in the ice due to vessel traffic. Most of the locations are oriented away from the prevailing wind direction during winter, although two of the locations, McKinley Bay and Sachs Harbour, are exposed to winds from the northwest and west during winter. Several of the ports would be susceptible to ice encroachment during summer and this would have to be considered in any harbour design.

# 3. ICE SUPPRESSION

## 3.1 Thermal Discharge

In areas where waste heat is available from industrial processes, it may be feasible to direct this heat into the area in which the ice growth is to be controlled. This may be accomplished by discharging warm water directly into the ice control area through a system of diffusers or nozzles.

### 3.1.1 Theoretical Considerations

For any arrangement which uses warm water discharge as an ice control technique, it is possible to generalize the associated heat balance equation in the following manner:

$$H = H_a + H_i + H_t + H_o$$

where

$H$ = heat input from warm water
$H_a$ = heat absorbed by ambient water
$H_i$ = heat transferred to the ice cover
$H_t$ = heat loss due to tides
$H_o$ = heat loss due to other factors.

This heat balance can also be expressed as

$$H = \rho CV \frac{dT}{dt} + \bar{K}T \qquad (1)$$

where

$T$ = the temperature above the freezing temperature of the receiving water (°C)

$\rho CV$ = the thermal capacity of the volume of water warmed by the thermal discharge (W-s/°C)

$\bar{K}$ = the total effective heat loss coefficient (W/°C)

$\bar{K}$ may be comprised of the following individual heat loss coefficients (depending on the characteristics of the ice control system and environmental factors)

-heat transfer to the ice in the ice control zone (or to the atmosphere if the area is to be kept ice free)

-heat loss by tidal flushing

-heat loss by conduction through any enclosure around the ice control zone or through the berth itself

-heat loss by advection through openings in the berth

-heat loss to the ice outside the ice control zone

-heat loss with water displaced during each ship arrival and departure.

From Equation (1), the buildup of the temperature of the warm water layer in the ice control zone is given by

$$T = \frac{H}{\overline{K}} \left(1-e^{-\frac{\overline{K}}{\rho CV}t}\right) \qquad (2)$$

The desired limiting ice thickness in the ice control zone dictates the heat transfer requirement to the ice cover, and this rate of heat transfer is determined by the characteristics of the boundary layer at the ice/water interface. Experiments with heat transfer in fluids have shown that these heat transfer characteristics may be expressed in the form of dimensionless numbers relating the thermal and dynamic properties of the fluid. The so-called Reynolds analogy is thus expressed as

$$\frac{Nu}{Re\ Pr^{1/3}} = f/2 \qquad (3)$$

where

Nu = Nusselt number equals $hl/k$
Re = Reynolds number equals $v\rho l/\mu$
Pr = Prandtl number equals $\mu C_{p}/k$
f = skin friction, or drag coefficient

and in the dimensionless numbers

h = convective heat transfer coefficient ($W/m^2$-°C)
l = characteristic length (m)
k = thermal conductivity of fluid (W/m-°C)
v = average velocity of layer (m/s)
$\rho$ = mass density ($kgm/m^3$)
$\mu$ = dynamic viscosity (kgm/m-s)
$C_p$ = specific heat at constant pressure $\left(\frac{W\text{-}s}{kgm°C}\right)$.

The friction factor (f) is defined in terms of the roughness characteristics of the ice (the Manning coefficient, n) and the hydraulic radius (r) of the warm water flow, and can be written as

$$f = \frac{19.6\ n^2}{r^{1/3}}$$

Substituting for the friction factor in Equation (3) results in

$$Nu = 9.8\ \frac{n^2}{r^{1/3}}\ Re\ Pr^{1/3}$$

and using the dimensionless number relationships and the properties of water at 0°C gives

$$h = 5.38\times10^6\ \frac{n^2 v}{r^{1/3}}\ \text{W-m}^2\text{-°C}$$

The heat lost in the boundary layer to the ice cover is then

$$H_1 = K_1 T \qquad (4)$$

where

$K_1$ = the heat transfer coefficient as above

This heat flow rate must equal the heat lost through the ice to the atmosphere to prevent further ice growth, and any excess heat transferred in the boundary layer will serve to diminish the ice thickness.

If the temperature buildup of the ambient water (T) is substituted from Equation (2) into (4), an expression for the rate of heat input to the ice control zone in order to maintain a desired heat flow to the ice cover over a specified time interval can be obtained. That is

$$H = \frac{H_1 \bar{K}}{K_1}\ \left[t + \frac{\rho CV}{\bar{K}}\ \left(e^{-\frac{\bar{K}}{\rho CV}t} - 1\right)\right]^{-1}$$

The heat losses due to other factors, in addition to that through the ice cover, are incorporated in the overall heat transfer coefficient $\bar{K}$.

For steady-state requirements, which are reached when the ambient temperature is built up to a level sufficient to maintain the desired ice cover, Equation (1) may be written as

$$H = \overline{K}T$$

By evaluating the various losses associated with the system, and thereby specifying $\overline{K}$, the required rate of heat input to the ice control zone can be determined.

### 3.1.2 Design Considerations

In optimizing the design of a thermal discharge ice management system, consideration must be given to a number of factors pertaining to the layout and sizing of the system for effective dispersal of warm water to the ice cover.

For example, probably the most efficient means of transferring heat to the ice cover would be to locate the discharge nozzles directly under the ice sheet and eject the warm water from the nozzles vertically onto the ice. By keeping the nozzle arrangement in close proximity to the ice cover, the heat loss to the ambient water could be minimized and the temperature of the water contacting the ice surface could be maintained at a higher level. This, together with higher plume velocities, would result in much more effective heat transfer to the ice cover without requiring a thermal barrier. This technique clearly requires that the system be lowered to the bottom during vessel arrival; on departure, the system would be brought back to the desired level. This would be accomplished by using flotation chambers attached to the piping system. A sketch of such an arrangement is shown in Figure 3-1.

The principle variables which must be fixed in selection of an appropriate submerged jet diffuser arrangement for ice management relate to the required rate of heat input to achieve the desired results. These are

- -number of jets (N)
- -diameter of jets (d)
- -initial velocity of jet discharge (v)
- -initial jet temperature to achieve the desired rise in ambient water temperature.

The heat flow rate from the discharge system is given by

$$H = \rho c Q \Delta T$$

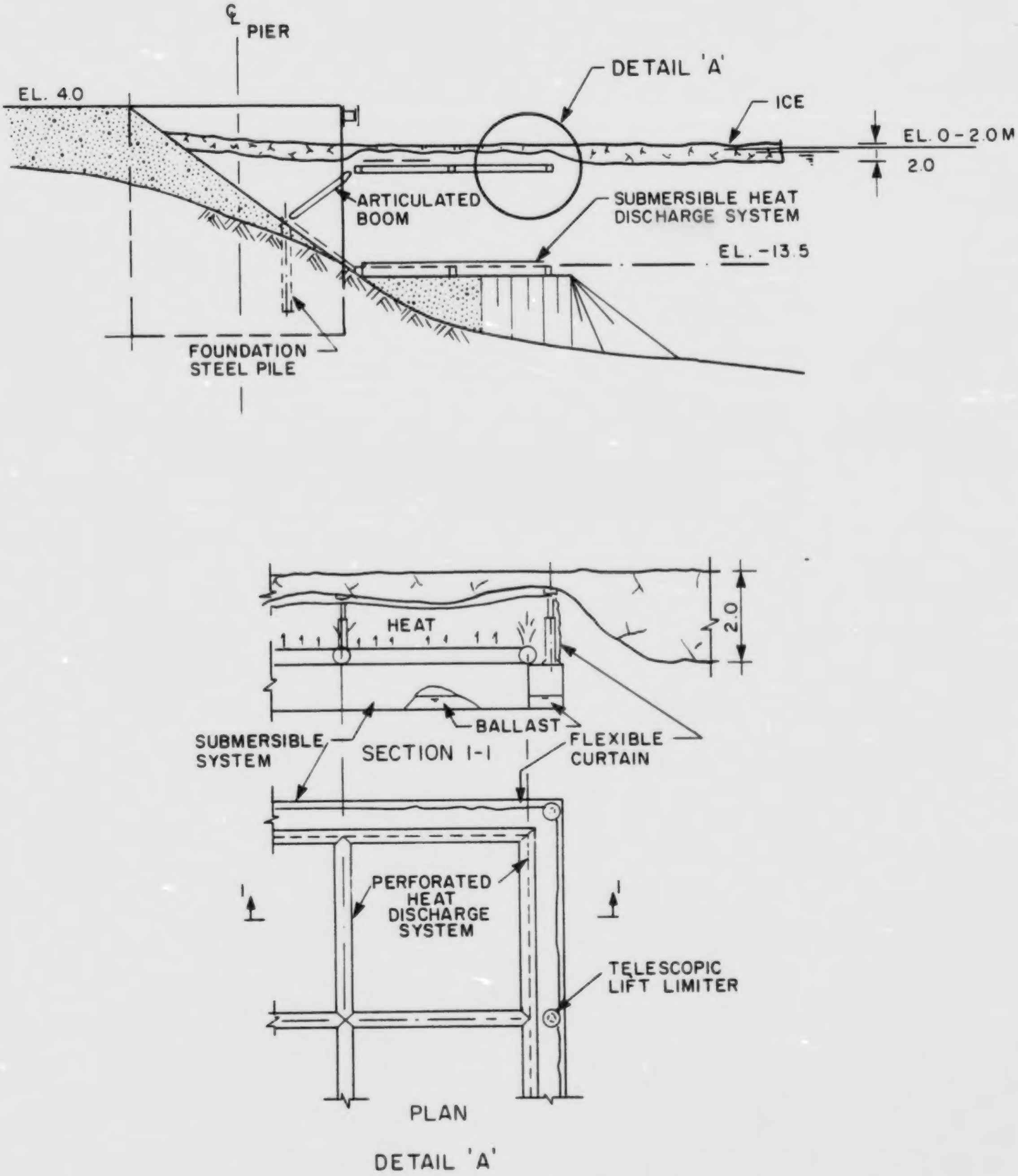

℄ PIER
DETAIL 'A'
EL. 4.0
ICE
EL. 0-2.0M
2.0
ARTICULATED BOOM
SUBMERSIBLE HEAT DISCHARGE SYSTEM
EL. -13.5
FOUNDATION STEEL PILE
HEAT
2.0
BALLAST
SUBMERSIBLE SYSTEM
SECTION 1-1
FLEXIBLE CURTAIN
1
1
PERFORATED HEAT DISCHARGE SYSTEM
TELESCOPIC LIFT LIMITER
PLAN
DETAIL 'A'

FIG. 3-1

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ACRES

THERMAL DISCHARGE CONCEPT WITH VERTICAL DIFFUSERS where

$\rho$ = density of the water
c = specific heat
Q = volume flow rate
$\Delta T$ = temperature difference between the discharge temperature and the ambient temperature of the receiving water.

For N diffusers, each of diameter 'd', the volume flow rate is

$$Q = N \frac{\pi d^2 v}{4}$$

and the heat flow rate is

$$H = \rho c N \frac{\pi d^2}{4} v \Delta T$$

The principle variables must then be selected in a combination to satisfy the heat requirements.

The power required to deliver the desired water flow rate can be expressed as

$$P = \frac{\rho Q v^2}{2} = \frac{8 \rho Q^3}{N^2 \pi^2 d^4}$$

In determining the required flow rates and associated power, consideration would have to be given to losses in the diffuser system due to friction, bends, etc, and normal piping design procedures would be used.

In addition to the principle variables, the diffuser designer must also fix the following variables:

-depth of submergence of the jets

-the spacing of the jets

-the ambient operating temperature where this in fact can be controlled by, for example, confinement of the ice control area

-direction of jet discharge, relative to the water surface.

Unlike the principle variables, the latter do not have a fixed interrelationship which must be honoured in their selection. That is, the choice of values for these variables is made on the basis of their influence in obtaining an appropriate heat flux distribution in the ice control area.

Overall, the design procedure would be:

-jet velocity and temperature are selected to obtain the required rate of heat input to the ice control area and rate of heat transfer to the ice cover

-the number of jets and their spacing are selected to give good coverage of the ice control zone, in recognition of the length and width of the warm water plume relative to the ice control area

-other variables (depth and inclination of the diffusers, etc) are then selected appropriately.

Certain other factors and practical considerations influence the selection of values for any of the design variables. These include the requirement that:

-the jets be sufficiently submerged to be free of ice action and therefore risk of blockage and/or damage

-the orientation and power of the jets be such that the diffuser arrangement does not require abnormal berthing manoeuvers, and ice control is not seriously impaired by the presence of a vessel in the berth

-the diffuser system be kept simple and readily accessible for servicing as appropriate in an arctic environment

-strong lateral and vertical mixing be developed in the management zone to promote uniform heat flux and to destabilize salinity gradients in the upper layer of the control zone

-acceptable temperature rises in the control area, from the environmental protection point of view, will be realized throughout all seasons of operation.

### 3.1.3 Precedence

While numerous examples exist of warm waste water from thermal power plants or industrial installations being discharged into ice-covered areas, there is little documentation on the design of such systems for the express purpose of minimizing an ice cover to facilitate navigation or ship docking. From the available information, the following applications have some relevance for the present discussion.

#### Saginaw Bay, Michigan
#### Ice Suppression Tests

A report by Carey (1977) describes an installation in Saginaw Bay, Michigan, in which warm waste water from an electric generating plant was discharged into a navigation channel to determine its effect on ice suppression. The system consisted of three sections of pipe of overall length

230 m installed at a depth of approximately 5 m. There was a 120-m section containing 21 equally spaced 5-cm diam nozzles aimed to discharge the warm water horizontally; a 55-m section containing 10 nozzles aimed to discharge water at an angle of 45 deg from the pipeline; and a 55-m section containing 10 equally spaced nozzles aimed to discharge the heated water vertically from the pipeline. A 186-kW pump was used to deliver the warm water at a rate of 7,000 L/min. When the system was turned on in mid-January, 1976, the ice thickness was 23 - 25 cm.

The temperature of the water above the nozzles was recorded so that the thermal plume could be located to determine the effectiveness of the arrangement. Testing showed that flow from the horizontal nozzles did not reach the surface but apparently flowed along the bottom, possibly due to increasing density of the heated water as it cooled. Consequently, no ice was melted by the water from these nozzles. Similar results were obtained with the 45-deg nozzles. Flow of warm water from these nozzles approached to within 3 m of the water surface at a horizontal distance of 4.5 m from the nozzles. Only the vertical nozzles achieved any degree of melting, this being indicated by the circular pattern of open water above each nozzle. When the vertical nozzles were turned on, the ice thickness was 43 cm thick, and in a period of 1-1/2 days, this ice was melted through. Temperatures during the time were a few degrees below freezing.

It was concluded that the expected results, substantial melt-through did not materialize although large amounts of heat were delivered by the system to the bay during the tests. The anticipated thermal plume either did not develop or was so small and weak as to be undetectable, and the heat in the effluent was rapidly diffused through turbulence and entrainment into the water mass of the bay. The velocity of the water jet from each nozzle probably became quickly damped, thus losing the momentum necessary to carry the jet to the ice cover.

Two possible approaches were suggested to overcome these deficiencies:

-use low velocity water jets coupled with an air-bubbler system to reduce turbulent diffusion of the warm water as it leaves the nozzles and to entrain it to the surface where it can melt the ice

-place the diffuser near the surface for an immediate melting action as the warm water leaves the nozzles.

Further tests using the first approach were considered unnecessary since bubblers had been proven effective in independent tests. The second approach was considered to be impracticable since it would interfere with navigation, and no further tests were conducted.

### Dome Petroleum
### Ice Control Tests

In 1977 and 1978, Dome Petroleum Limited carried out a number of model and full-scale studies to investigate means of maintaining an open area of water around a vessel to facilitate drilling in landfast ice. One technique considered was the use of thermal discharge in the form of cooling water from the drilling engines. It was determined from theoretical considerations that sufficient waste heat was available to maintain an open area around the vessel if it could be efficiently transferred to the ice cover. In the tests, water was heated in a large boiler and was discharged through a series of nozzles to a test area adjacent to a supply ship in Tuktoyaktuk Harbour during the winter of 1978. No information is available on the quantities of heat discharged; however, it was found that this discharge had a negligible effect on melting the ice cover. It was concluded that the warm water was simply being entrained by the ambient water and was moved away from the test area without allowing for a rise in the ambient temperature.

### Bridport Inlet
### Ice Management Design

As a part of the design of the ice management system for the Arctic Pilot Project proposed LNG terminal at Bridport Inlet, Melville Island, detailed studies have been conducted to investigate the use of the waste heat from the liquefaction process in controlling ice thickness in the berthing area near the dock (Acres, 1978). The total rate of heat output available from the cooling water is 111 MW, and it was determined that only a fraction of this would be required to maintain manageable ice thicknesses near the dock if an enclosure could be implemented to allow a thermal reserve to be built up. Numerical model studies showed that without such an enclosure, a sufficient increase in ambient water temperature could not be attained.

Recent studies have shown that probably the best way to provide the necessary enclosure is to use the area under the dock which would be designed to allow the ice to be pushed there by the berthing ship (Acres, 1982). The ice would then be melted before the next ship arrival. The ice management area under the dock is 450 m long and 30 m wide. The diffuser arrangement is such that warm water would be sprayed on top as well as underneath the ice with any excess warm water being directed to the berthing area at the front of the dock (Figure 3-2). The costs of piping for this arrangement were estimated to be in the order of $1.5 million in 1981.

### Raahe, Finland

At Raahe, discharges from three sources are directed into the harbour and surrounding manoeuvering basin. The total discharge rate is 187 MW which comes from generating,

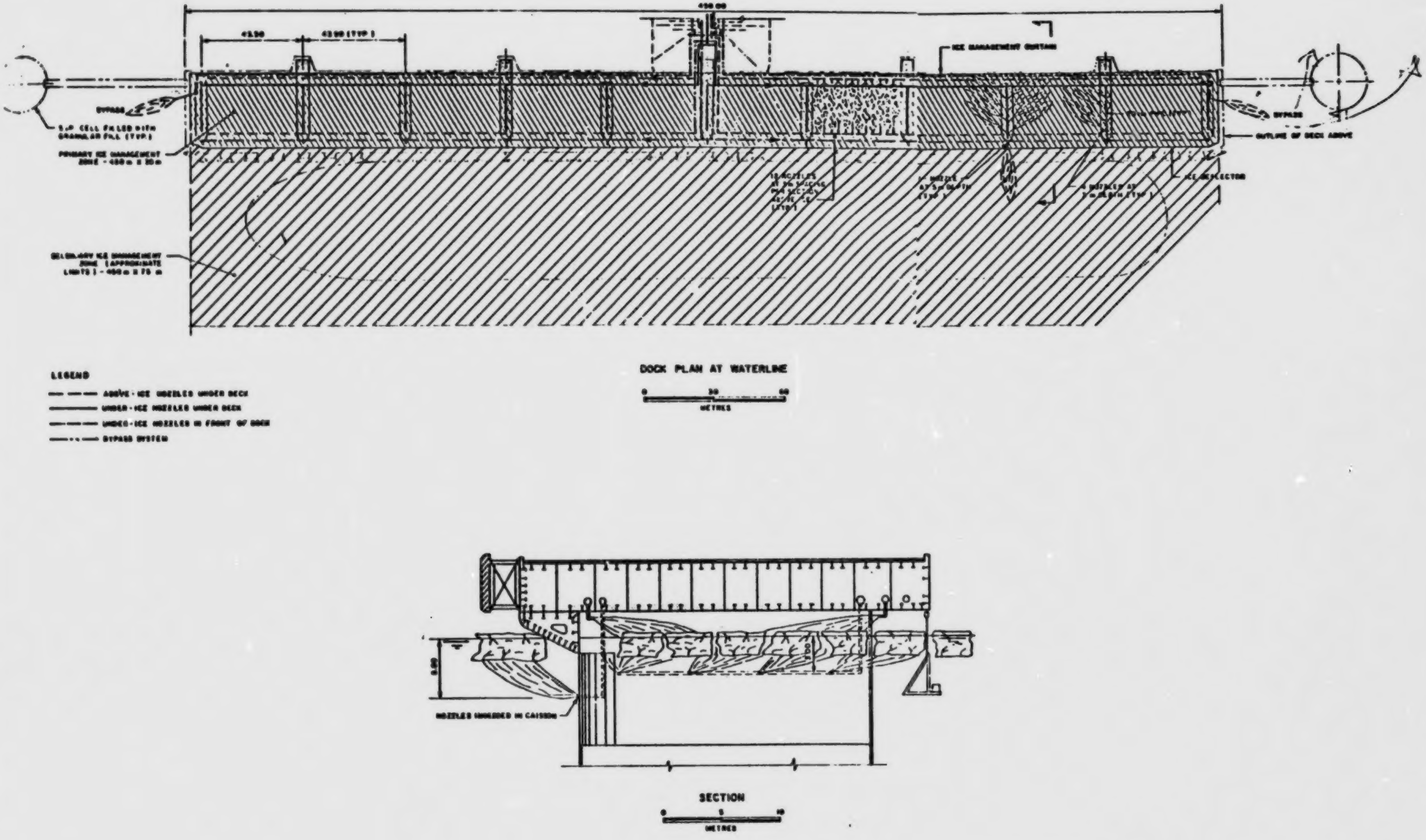

450.00
43.30
43.30 (TYP.)
ICE MANAGEMENT CURTAIN
BYPASS
S.P. CELL FILLED WITH GRANULAR FILL (TYP.)
PRIMARY ICE MANAGEMENT ZONE - 450 m X 30 m
SECONDARY ICE MANAGEMENT ZONE (APPROXIMATE LIMITS) - 450 m X 75 m
OUTLINE OF DECK ABOVE
ICE DEFLECTOR
NOZZLE AT 5 m DEPTH (TYP.)
LEGEND
ABOVE-ICE NOZZLES UNDER DECK
UNDER-ICE NOZZLES UNDER DECK
UNDER-ICE NOZZLES IN FRONT OF DOCK
BYPASS SYSTEM
DOCK PLAN AT WATERLINE
0
30
60
METRES
NOZZLES IMBEDDED IN CAISSON
SECTION
0
5
10
METRES

FIG.3-2

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ICE CONTROL CONCEPT FOR ARCTIC PILOT PROJECT iron works and steel plants. The discharge is simply dumped into the harbour with no attempt being made to distribute it in any way. The main shipping berth, measuring over 20 000 $m^2$, and most of the basin, is kept completely open during the winter. Ice at the basin extremities advances and recedes depending on air temperatures. The success in keeping this area ice free is attributed to the high degree of enclosure of the basin and harbour since other areas in Finland with larger heat inputs from industrial sources do not experience similar results due to their being more open to the outside sea.

## 3.2 Bubblers

Bubblers operate on the basis of entraining relatively large quantities of water in an air plume generated by compressed air, usually for the purpose of transporting warm water at depth to an ice cover, thereby retarding ice growth. In addition to this application, which has been used in water bodies with a natural thermal stratification, bubblers may also be used as a means of

-increasing heat transfer to an ice cover in areas of an artifically-generated heat reserve (for example, in conjunction with a thermal discharge)

-providing a barrier to heat loss through water flow in thermal discharge systems by generating a countercurrent (a pneumatic barrier)

-providing a barrier to the movement of ice pieces

-reducing friction at the hull of ice-breaking vessels by washing the hull with entrained water.

Two types of bubbler arrangements have been used in the common application of retarding ice growth through the movement of warm water at depth to the surface. In the continuous bubbler system, a perforated pipe is placed on the bottom or at depth, and is connected to an air compressor. As the air bubbles rise from the pipe through the water column, they entrain water and form a plume which, at the surface, has a diameter approximately equal to the submerged depth of the pipe.

In "burper" systems, a special patented nozzle is placed at the bottom of a vertical, large diameter pipe, and a large bubble of air is emitted at intervals of a few seconds. As the bubble rises in the pipe, a flow is induced to carry water from the bottom to the surface. The surfacing of the large bubbles creates a turbulent zone which inhibits ice formation. In water bodies which have a thermal reserve, the burper will also retard ice growth by transferring warm water to the surface as in the case of the continuous bubbler system.

### 3.2.1 Design Considerations

When designing a bubbler installation, one should consider a number of factors such as the geometry and topography of the site, the degree of water movement, the climate, and most essential, the natural thermal regime of the site. While in theory, freshwater bodies have water at a temperature of 4°C at the bottom, in actual fact, it is most unlikely that such a temperature exists except possibly in very deep or smaller sheltered lakes. A more likely temperature for most lakes is less than 0.5°C, and rivers, because of the thorough mixing, will have almost uniform temperatures (very close to 0°C) throughout the depth. Given a sufficient reserve however, even a small temperature difference can be effective in preventing ice growth or in melting an existing ice cover.

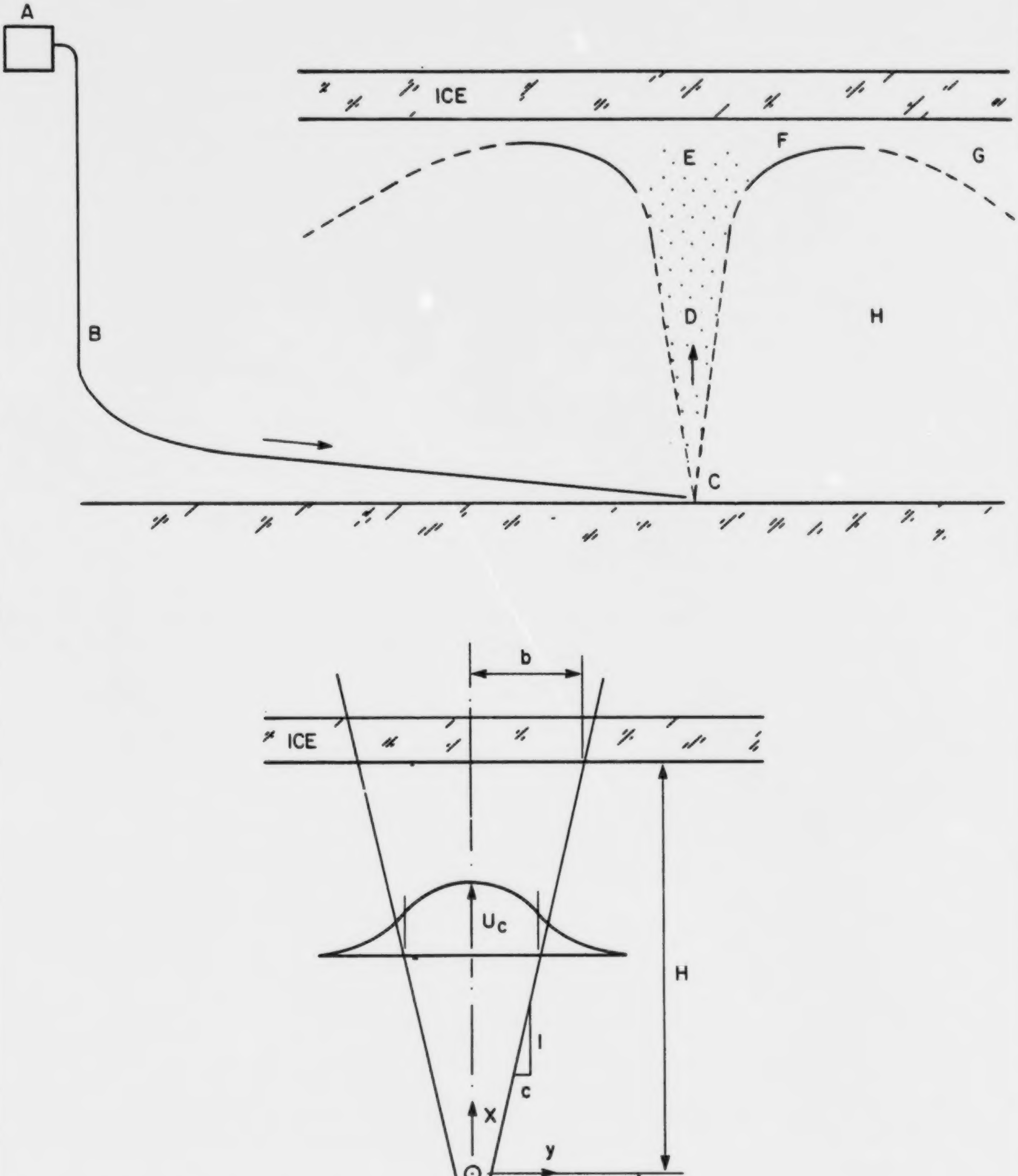
In determining the bubbler design, a knowledge of the winter climate of the site is essential to ascertain the heat loss to the atmosphere through the ice cover. This is best done through a record of the freezing degree-days for the site. The rate of heat transfer can then be determined over the winter, and the required heat flow rate from the bubbler to the ice can be determined to maintain a certain minimum ice thickness. Other climatological factors, such as snow cover, winds and solar radiation, should also be considered when determining the heat loss rate to the atmosphere. Records of natural ice growth for the site over a number of years would be particularly valuable for design purposes.

Potential hazards to an installed system should also be considered in the design state. These hazards would relate to possible damage from ships or moving ice which may be caused to ridge to considerable depths.

### 3.2.2 Theoretical Considerations

The mechanics of a two-dimensional vertical plume induced by rising bubbles from a line-source bubbler system have been described in some detail by Ashton (1974). The analytical treatment follows classical free turbulent jet analyses with suitable modification to account for the driving force of a bubbler plume which is due to the buoyancy flux deriving from the buoyant force of the bubbles. The vertical velocity is represented by a Gaussian distribution (as shown in Figure 3-3) with a lateral spreading which proceeds linearly in the vertical direction. The centerline velocity may be written as

$$v_c(y) = \frac{[-P_a\ Q_a\ \ln(1-y/d^*)]^{1/2}}{\sqrt{\pi \rho_w v_b c(y+y_o)}}$$



A
ICE
B
E
F
G
D
H
C
b
ICE
$U_c$
H
1
c
x
y
$x_0$

FIG. 3-3

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

SCHEMATIC DRAWING
OF A BUBBLE SYSTEM AND COORDINATE SYSTEM FOR ANALYSIS

where

$v_c(y)$ = centerline velocity at distance y above the bubbler
$P_a$ = atmospheric pressure
$Q_a$ = volume flow rate of air per unit length of bubbler pipe
= water density
$v_b$ = mean rising speed of the air bubbles
$c$ = rate of linear spread of the distribution
$y_o$ = the distance from the bubbler to an analytical origin which accounts for the initial momentum of the air jet, local orifice geometry, and flow conditions in the initial region which differ from those in the established region of induced flow. From experiments, $y_o$ was found to have a mean value of 0.8 m with variations of tenths of metres.
$d^*$ = $d+P_a/\rho_w g = d+10.3$ (in SI units for sea level conditions)
$d$ = the bubbler depth.

From experimental data, $v_b$ was found to be a weak function of the air discharge rate and may be written as

$$v_b = c_b Q_a^{0.15}$$

where

$$c_b = 2.14 \text{ m}^{0.7}\text{s}^{-0.85}$$

The rate of spread of the plume was also found to be described by

$$c = C_c Q_a^{0.15}$$

where

$$C_c = 0.182 \text{ m}^{-0.3}\text{s}^{0.15}$$

The induced volume flow rate of water may be written as

$$Q_w(y) = \sqrt{2\pi}\ v_c\ c(y+y_o)$$

Substituting for $v_c$, c and $v_b$ yields the induced volume flow rate of water at height y = d as

$$Q_w(d) = \sqrt{2\pi}^{0.25} \frac{P_a C_c}{\rho_w C_b}^{0.5} Q_a^{0.5} (d+y_o)^{0.5} [-\ln(1-\frac{d}{d^*})]^{0.5}$$

A plot of $Q_w(d)$ as a function of $Q_a$ and d is shown in Figure 3-4.

The width (diameter) of the impinging jet at the surface is given by

$$2b = 2c(d+y_o) = 2\ C_c Q_a^{0.15}(d+y_o)$$

where

b = the standard deviation of the velocity profile at the plane of the surface.

The heat transfer to an ice cover from a water jet flowing perpendicular to the surface may be written in terms of dimensionless numbers as (for water properties at 0°C)

$$Nu = 0.96\ Re^{0.62}$$

where

$Nu$ = Nusselt number = $\frac{hx}{k}$

$Re$ = Reynolds number = $\frac{u_c x}{\nu}$

$h$ = heat transfer coefficient at the ice/water interface
$k$ = thermal conductivity of the water at the interface
$\nu$ = kinematic viscosity of water.

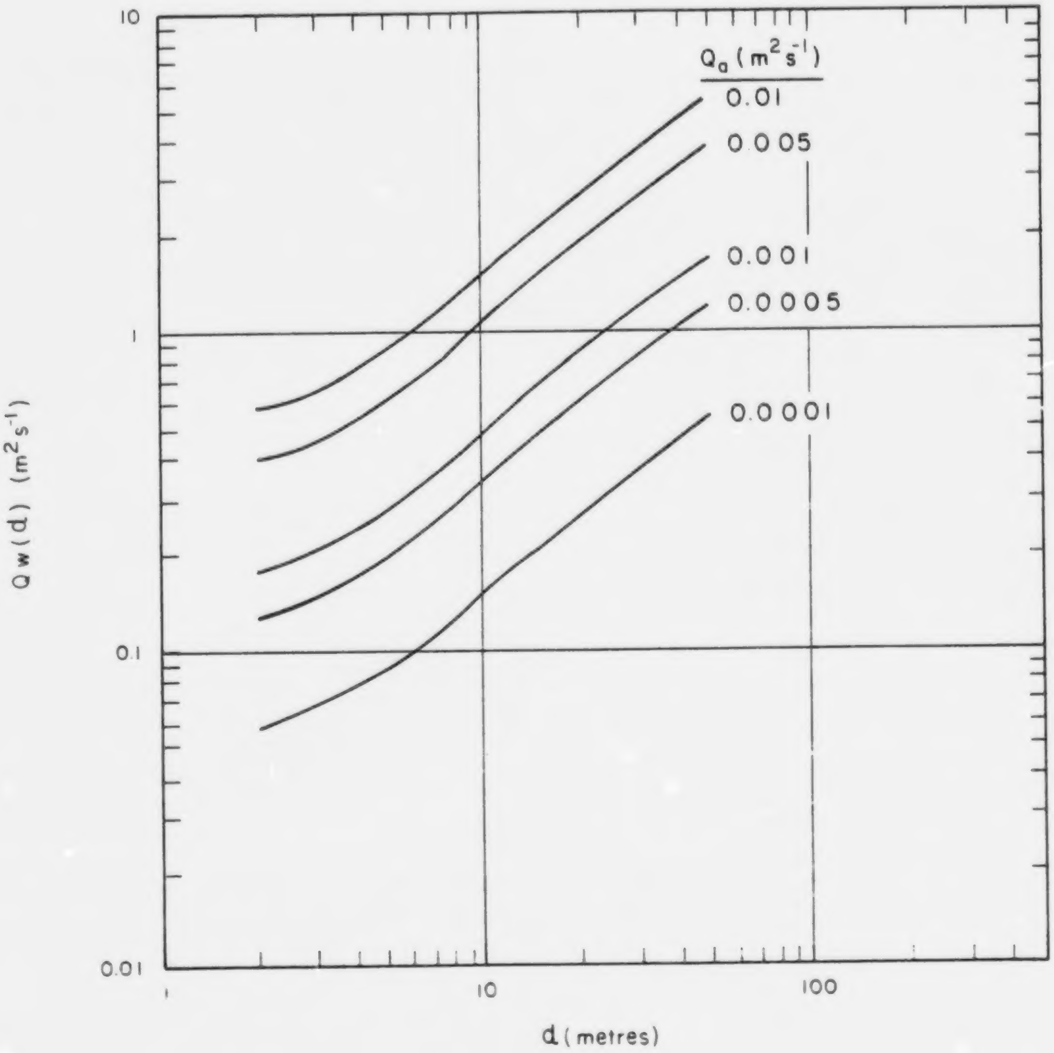
Making substitutions, we have for the heat transfer coefficient in the impingement zone ($x = b$)

$$h_b = \frac{0.96\ k \nu_c^{0.62} b^{-0.38}}{\nu^{0.62}}$$

and the heat transfer coefficient outside the impingement zone may be written as

$$h(x) = h_b \left(\frac{x}{b}\right)^{-0.38}$$

For water at 0°C, $h_b = 1{,}920\ v_c^{0.62}\ b^{-0.38}$ (SI units).



FROM ASTON, 1974

FIG 3-4

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

INDUCED SURFACE FLOW AS A FUNCTION OF BUBBLER DEPTH AND AIR DISCHARGE RATE

The heat transferred to the ice cover in the impingement zone is then

$$q_b = h_b(T_w - T_i)$$

where

$T_w$ = the temperature of the impinging flow
$T_i$ = the temperature at the ice surface.

Similarly, the heat transferred to the ice surface outside the impingement zone may be obtained by determining the local heat transfer coefficient h(x). Alternatively, in determining the air flow requirements for an installation, one can determine the necessary heat flow to the ice cover to maintain certain desired conditions and, hence, the jet velocity and volume air flow rate ($Q_a$).

### 3.2.3 Use of a Bubbler as a Pneumatic Barrier

A bubbler may be used in conjunction with a thermal discharge to provide a barrier to the flow of warm water beyond the ice management zone and, thereby, assist in promoting the buildup of a thermal reserve. The currents induced by the bubbler in the warm water layer must therefore be large enough to counteract those set up by warm water discharge. At the same time, it is important to prevent the bubbler plume from diluting the warm water layer to an extent that the temperature is reduced below the desired minimum for heat transfer to the ice cover. This may happen because of the large quantities of cold water entrained by the bubbler plume during its rise through the water column, particularly in saline water where the temperature structure is often constant throughout the water column.

The compressor air flow requirements for such an installation may be determined from a knowledge of the counter-current that is necessary to contain the warm water discharge and then by applying a relationship for air flow rate in terms of horizontal surface velocity. The air flow rate required to produce the barrier design velocity is given by Herbich (1974) as

$$Q_a = \frac{0.3\, v^3_{max}}{g}$$

where

$v_{max}$ = the design barrier velocity
$g$ = the acceleration due to gravity.

Since the relationship is cubic, a small increase in current requirements results in very large increases in air flow rate and associated compressor power.

### 3.2.4 Precedence

The application of air bubblers to create ice free conditions in freshwater is common. Installations in seawater have been generally unsuccessful, although there are isolated examples of limited success due to the movement of more saline water from the bottom. Of the numerous descriptions of bubbler installations, the following are selected because they present some detail on system parameters and specifications.

### Narssaq, Greenland

A bubbler system was installed in Narssaq Harbour on the southwestern tip of Greenland from October 30, 1966, to February 27, 1967, to reduce the amount of ice formation in the harbour due to river runoff (Hulgaard and Sorensen, 1971). Two 100-m sections of 2.5-cm plastic tube with 0.6-mm holes at 2-m centers were placed on the bottom and air was supplied from a standard compressor at a rate of 4.5 $m^3$/min. It was found that during relatively mild conditions, holes with diameter 1 - 1.5 m were formed in the ice directly over the bubblers. When the temperature dropped to -10°C, these holes were reduced to 0.5 m diam or were completely closed in some cases. However, the ice was significantly thinner above the bubblers than elsewhere. It was concluded that a significant improvement could be achieved by means of a properly designed air bubbler arrangement and that acceptable navigation conditions could be maintained through the winter.

### Tuktoyaktuk, Northwest Territories

Ince (1963) reports on a bubbler system that was installed at the face of the dock in Tuktoyaktuk Harbour in 1959 to reduce ice growth around the dock structure, thereby lessening the vertical forces exerted on the piles due to tidal action on the ice. The bubbler operated successfully and no further damage was reported. The success of the bubbler was attributed to the existence of a dense, warmer layer near the bottom. The bubbler line consisted of a 2.5-cm plastic hose with 1.6-mm holes at 2.4-m centers running 12 m along the dock face at a depth of 4.5 m.

### Sugar Island, Sault Ste. Marie, Michigan

A bubbler was installed in 1971 at the mainland dock of the Sugar Island ferry at Sault Ste. Marie, Michigan, for the purpose of keeping the slip ice free. The bubbler consisted of two compressed air circuits, one supplying air at 0.3 $m^3$/min, the other at 3 $m^3$/min. The line had orifices of 10-mm diam spaced at 2 m and was installed at a depth of 27 m. The bubbler was successful and was reinstalled in following years.

### Duluth Harbour, Minnesota

A bubbler system was installed in Duluth Harbour in the winter of 1971 as a part of the Great Lakes and St. Lawrence Seaway Navigation Season Extension Demonstration Program. The bubbler line formed a rectangle 490 m long and almost 300 m wide and consisted of polyethylene pipe 38 mm diam with 1.2-mm diam orifices at 4.6-m intervals. The water depth ranged from 9 - 12.5 m, and the bubbler was installed at a depth of 8.2 m. The bubbler created open water areas of about 7.5 m diam above the pipe with reduced ice thicknesses extending back from the open areas. The result was that this area could be transitted much more easily than the ice outside the test area. In 1972, a bubbler system of total length 1,430 m was installed and operated at pressures of 200 - 270 kPa. The system was successful in reducing ice growth in the bubbler area with thicknesses of 10 cm being measured at a distance of 7.6 m from the line of the bubbler. Beyond the influence of the bubbler, ice thicknesses of up to 50 cm were observed.

### Thunder Bay

A bubbler system was installed in one of the grain elevator slips in Thunder Bay in late January 1980 and ran until March 25, 1980 (Hill, 1980). The total line was 1,200 m long and had orifices of 1.6-mm diam spaced at 6-m intervals along the pipe. The compressor delivered air at a rate of 9 $m^3$/min and a pressure of 690 kPa which was regulated to give the desired pressure in the bubbler line. Ice thicknesses in this slip decreased while ice in other slips grew to a maximum thickness of 91 cm. The result was that the harbour tug had a much easier task breaking ice in the test slip than in the other areas.

Further study of the effect of bubblers in Thunder Bay was undertaken in 1982 as a part of the Canadian government's aim to develop alternatives to the conventional icebreaker as a means of ensuring an official opening date for the port. Both the conventional air bubbler and the air cannon mixer (burper) were tested. The bubbler consisted of two lines of galvanized pipe running the full length of a slip; one line 3.8-cm diam was run along the dock face, the other with 2.5-cm diam in the center of the slip. The lines were fed by two compressors delivering air at a rate of 10 $m^3$/min at a pressure of 620 kPa. The units were started up on March 1, 1982, when the ice in the slip was 60 - 120 cm thick with the thicker ice near the dock face. By late March, open water existed practically all along the dock face and out for a distance of 3 - 4 m. The center of the slip over the outside bubbler line also showed similar areas of open water. Comparison with theoretical calculations based on Ashton's (1974) work indicated reasonable agreement (V. B. Cook, 1982).

Five air cannon mixer units were installed in another slip; three units were installed along the dock face and two in the middle of the slip. The total power consumption was 3.8 kW, and the operating pressure was 100 kPa. The units were installed on March 4, 1982, through holes 1.2 $m^2$ which were cut in the ice. By late March, those holes near the dock were about 6 - 9 m diam, while those in the middle of the slip were about 3 m diam. The ice at the periphery of the holes was still relatively thick as compared with the ice around the holes over the conventional bubbler which showed a tapering of the ice away from the open water. The cannon mixers appeared to cause a rapid downturn in the water without effecting much lateral spreading at the surface.

A comparison of the ice melting rates per unit air flow indicated that the air cannon mixers were approximately 30 percent as effective as the conventional line bubbler. However, the air cannon mixers were easier to install and remove than the line bubbler. It was also considered that they would be less vulnerable to damage from propeller wash or anchors during the shipping season (V. B. Cook, 1982).

### 3.3 Wave-Making Devices

Wave-making devices have been suggested as a means of controlling ice growth in harbours, the primary emphasis for this approach being due to P. F. Andersen (1977, 1981). The wave action induced by the device develops sufficient agitation of the water surface to prevent the formation of a solid ice cover. Instead, large quantities of frazil ice are formed and these, while being prevented from congealing to produce a stationary cover, are moved away from the ice control area by the wave action.

#### 3.3.1 Theoretical Considerations

The power requirements of a particular installation are determined from considering the theory for deep water waves. Andersen (1981) suggests that for water in excess of 6 m in depth, waves of length up to 25 m may proceed as deep water waves. For deep water waves, the wave celerity (c) is related to wave length (L) by

$$c^2 = gL/2\pi$$

where

g = acceleration due to gravity

and the total mean energy per unit surface area can be written as

$$E = \frac{1}{8} g\rho H^2$$

where

$\rho$ = density of water
$H$ = wave height.

The energy progresses with a velocity of half the wave velocity, and the effective power output of the wave machine to maintain the progressive wave system is written as

$$P_{eff} = \frac{1}{8} g\rho H^2 \times \frac{1}{2} c\ell$$

where

$\ell$ = length of the wave board or plunger.

The mass transport of water in the direction of wave propagation is an inherent feature of wave action, and the velocity of transport is given by

$$v_{max} = \left(\frac{\pi H}{L}\right)^2 c e^{-4\pi z/L}$$

where

$z$ = the water depth and H/L represents the steepness ratio of the waves, the latter depending on the type of wave-making device employed.

The capacity of the wave train for transporting surface-formed ice depends on the velocity of transport and the capacity of the surface waters to hold the ice formed in suspension. As the amount of ice in the wave train increases, a larger proportion congregates near the surface, and the layer extending from the surface to the level at which the energy level is halved, coinciding with the halving of the mass transport velocity, contains a large majority of the suspended ice. Andersen (1981) calls this layer the "active layer" and defines the "reach" of the wave train as the distance covered by the mass transport in the time that the ice content of the active layer has reached 10 percent.

Andersen (1977) reports that the amount of ice formed under wave action is in the order of 0.25 kg/h/$m^2$ of surface for each 1°C that the air temperature is below the freezing point. Based on this result, and an average velocity of mass transport within the active layer of 2 percent of the wave celerity, he suggests the "reach" of the wave train for a steepness ratio of 1:20 is given by

$$R = 1{,}580 \frac{Lc}{\Delta T}$$

where

$R$ = reach (m)
$L$ = wave length (m)
$c$ = wave celerity (m/s)
$\Delta T$ = temperature decrease below the freezing point (°C).

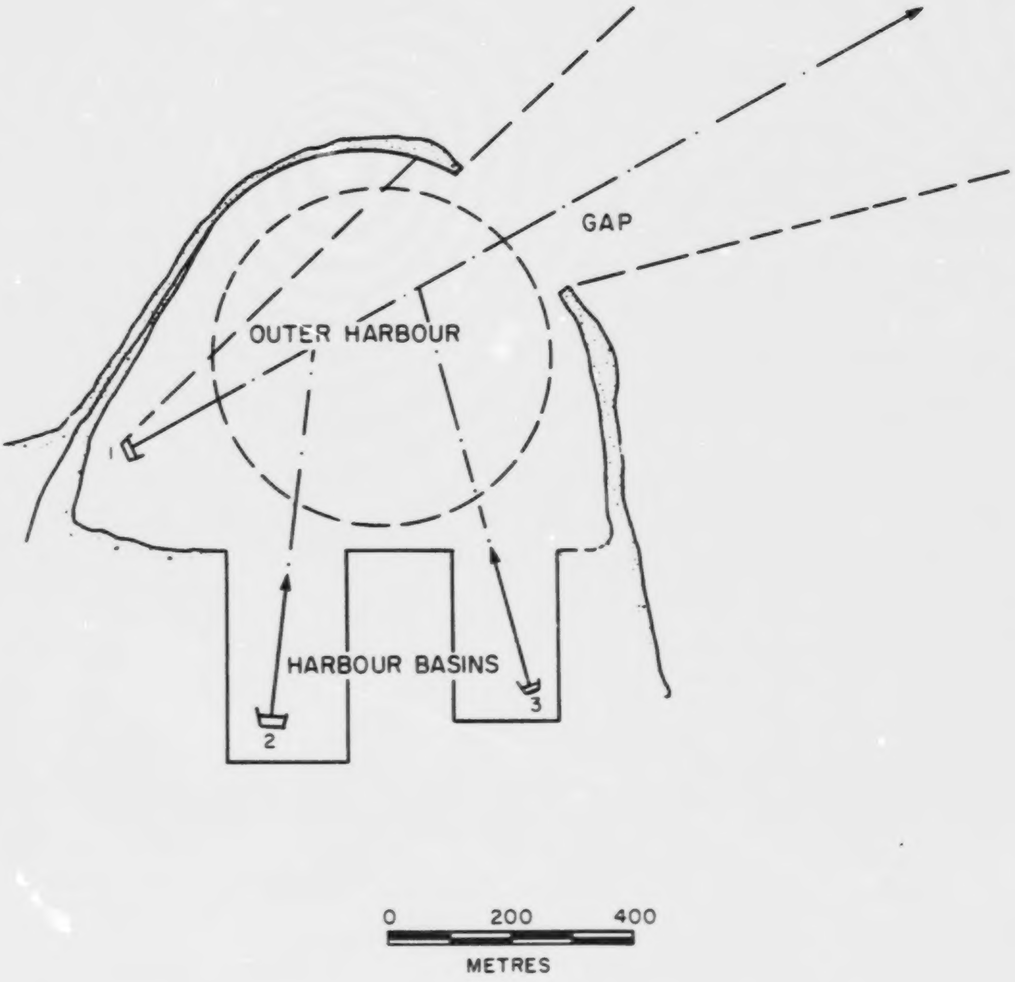
It is estimated that waves approximately 1 m high and 10 - 12 m long would be able to transport ice several kilometres without hampering harbour operations. A possible installation of a wave generator system is shown in Figure 3-5. Power requirements of the system are 20 kW for Units 2 and 3, and 75 - 150 kW for Unit 1, depending on seaward conditions.

Table 3.1 shows ice clearing ranges (at -30°C), power rating, and capital and operating costs for various wave generators.

TABLE 3.1

WAVE GENERATOR DATA

| Wave Characteristics | | | Wave Train | | Wave Machine Installation | | | |
|---|---|---|---|---|---|---|---|---|
| Period T (s) | Length L (m) | Height H (m) | Breadth (m) | Minimum Range of Ice Clearing (m) | Displacement (tonnes) | Horsepower (kW) | Equipment Cost ($) | Power-Cost/month ($) |
| 1.5 | 3.51 | 0.35 | 24 | 433 | 10 | 7 | 30,000 | 400 |
| 1.75 | 4.78 | 0.48 | 30 | 689 | 28 | 19 | 84,000 | 1,100 |
| 2.0 | 6.24 | 0.62 | 42 | 1 030 | 48 | 34 | 144,000 | 2,000 |
| 2.25 | 7.37 | 0.74 | 48 | 1 280 | 95 | 67 | 285,000 | 4,000 |
| 2.5 | 9.75 | 0.98 | 60 | 2 010 | 193 | 194 | 579,000 | 11,000 |
| 3.0 | 14.0 | 1.40 | 90 | 3 470 | 600 | 731 | 800,000 | 42,000 |
| 3.5 | 19.1 | 1.91 | 120 | 5 510 | 1 480 | 2 000 | 4,400,000 | 120,000 |
| 4.0 | 25.0 | 2.50 | 165 | 9 870 | 3 160 | 4 800 | 9,500,000 | 275,000 |


GAP
OUTER HARBOUR
1
HARBOUR BASINS
2
3
0
200
400
METRES

SOURCE:
ANDERSON, 1981

FIG 3-5

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

EXAMPLE INSTALLATION OF WAVE-MAKING DEVICES

ACRES

### 3.3.2 Precedence

#### Rainy Lake, Ontario Tests, 1962

The first experiments using wave machines were carried out on Rainy Lake in northern Ontario during December 1962 (Andersen, 1977). Waves were produced by an oscillating plunger which consisted of a 10-cm x 10-cm pine log, 3 m long, equipped with end plates and small weights for stabilization. Power was delivered by a 0.2-kW electric motor.

During the first 3 hours of operation, the waves broke up and melted the ice, which was 1 cm thick, in a path 8 m wide and 25 m long. During the following week, in which the plunger was operated 24 hours a day, this area remained ice free even though the air temperature went as low as -30°C (-22°F) and there were periods of snow.

#### Quesnel, British Columbia Tests, 1968

A floating wave machine was tested in a small lake near Quesnel, British Columbia, in late April 1968 (Andersen, 1977). The machine was powered by a variable speed, 0.4 kW, electric motor. The weight of the machine was 170 kg of which 35 kg was a moveable weight which by an adjustable crank could be given relative vertical oscillations with amplitudes ranging up to 25 cm. By attaching various size pontoons to the wave machine, it was possible to create waves of different sizes and periods.

At the time of installation, the ice cover on the lake was 40 cm thick and honeycombed due to melting. The air temperature during the test was approximately +10°C. Using a stroke of 1.2 seconds, the wave machine melted the ice within a radius of 100 m after 4 hours of operation. The following day, most of the lake ice was melted by wind-driven waves. Neighbouring lakes remained ice-covered for another week.

#### Frederikshavn, Denmark Installation

Two wave-making machines were installed in Frederickshavn Harbour in Denmark during the winter of 1981 (Andersen, 1981). Each unit is 6 m wide with a displacement of 2.5 tonnes and power of 2.2 kW. Each is designed to produce waves of 3.5 m in length, 0.35 m in height and period 1.5 seconds. While their performance in ice was not tested because significant ice conditions did not develop, the tests showed that practical and durable wave machines could be built and that the energy efficiency of wave generation was close to 100 percent.

### 3.4 Ice Dusting

Both laboratory experiments and field operations have shown that dusting of ice surfaces with coal dust or other dark granular material can increase the absorption of solar radiation and so increase the rate of melting of the ice. Formulae have been derived to determine the change in albedo (the percentage of reflected radiation) and intensity of surface melting due to dusting.

### 3.4.1 Theoretical Considerations

According to Zotikov and Moiseeva (1972), a typical value for the required change in albedo, $A_d/A$, is 0.3, where $A_d$ equals the albedo of the covered ice and A equals the albedo of the original ice. The ratio of that part of the surface to be covered by particles to the total melting surface is taken as 0.7.

For these requirements, dusting rates for two different particle diameters have been established. For a diameter of 0.5 mm, the dusting rate is 0.20 $kg/m^2$; and for a diameter of 0.2 mm, the rate is 0.070 $kg/m^2$.

Air temperature and the amount of sunshine during the early stages of breakup are critical factors in ice dusting operations. Ice dusting is not very effective if the daily minimum air temperature falls much below 0°C. If the air temperature is too low, heat losses from the surface by convection, evaporation and long-wave radiation will offset the increased solar energy absorbed by the darkened ice surface. Approximate calculations, based on the amount of solar radiation during the breakup period, indicate that dusting can increase melting rates up to about 1 cm/d in latitudes of 45°N and up to 2 - 3 cm of ice a day in latitudes of 70° - 80°N (Williams, 1970). Several days of weather conditions conducive to increasing melt rates are needed to decrease significantly the length of the breakup period or weaken thick, stable ice covers. The effectiveness of dusting is decreased by snow accumulation and melt puddles, the latter actually decreasing the albedo by essentially the same amount as the dust.

Successful dusting operations require detailed studies of past weather records, past ice conditions and dusting techniques. Information is needed on the frequency of new snowfall during potential dusting periods, the availability of suitable dusting material, and the cost of transporting and applying the dust. If potential benefits exceed anticipated expenditures, large-scale trials may have to be carried out before the most effective technique is developed for a site.

### 3.4.2 Precedence

#### Fairbanks, Alaska

Ice dusting was carried out on the Chena and Tanana rivers in Alaska during 1965/66 with the aim of expediting the natural spring breakup and, therefore, reducing serious ice jamming. The maximum ice thickness was approximately 0.45 m. A converted aircraft sprayed 35 tonnes of fly ash and coal dust in 10 hours of flying time. The size of the material indicated an average particle size of approximately 0.5 mm. The mean daily temperatures during the dusting operations were from -10° to +7°C.

The result of this operation promoted the breakup of the dusted channel in advance of the rest of the river by 9 days. During the test period, there was no new snowfall. The researchers, Cook and Wade (1968), concluded that further field work should be undertaken to determine the degree of feasibility.

### Inuvik, NWT

Ice dusting trials were carried out during 1964 for the purpose of comparing several different dusting techniques at a northern site where weather conditions were favourable for ice dusting, and also for determining the maximum depth of penetration of different dusts and the minimum air temperature at which dusting would be effective. The site was at Long Lake, NWT, which is approximately 2.5 km long and 0.75 km wide, and ice thickness was generally 1 m. The range of solar radiation available was between 190 and 290 $W/m^2$ and the average daily temperatures during the testing period ranged from -12° to +10°C.

Results of the tests were more qualitative than quantitative because of the problems in measuring ice thickness due to the deteriorated state of the melting ice (Williams, 1970). The conditions most favourable for ice dusting occurred when the minimum temperatures were between -5° and 0°C. Williams stated that, if the night temperatures went below -4°C, then freezing at night would offset the increased melting during the day.

### Milne Inlet, Baffin Island

Observations on the effect of ice dusting on sea ice were carried out at Milne Inlet during 1965. Two test areas of about 230 $m^2$ were used. In one area, the snow cover was removed before the cover was dusted and, in the second, the dust was sprayed directly on top of the snow cover.

The ice cover was 1.5 m thick at the time of dusting on May 11. By June 18, water depth over the sprayed sites was 55 cm, while the depth of water on the undusted areas was about 5 cm. In some places, sand blown from the shore had formed melted holes 10 cm diam and 40 cm deep.

Conclusions reached after the observations at Milne Inlet were

-a probable reduction of 0.5 m of the ice cover thickness could be achieved in the 1-mo period to June 20

-even at high latitudes with long hours of sunshine, the effect of dusting is significantly reduced if air temperatures go below 0°C

-coarse dusting material is more effective than fine dust.

### Thunder Bay, Ontario

Grain dusting was one of a number of ice control techniques tested in Thunder Bay harbour during the winter of 1982. The density of the dust application was approximately 0.02 $kg/m^2$. Although the dusted areas contributed to a reduction in ice thickness, it was difficult to arrive at a firm conclusion as to the effectiveness of the dust because of the complex weather conditions (Miller, et al, 1982).

### 3.5 Insulation

A suitable insulation placed on a relatively thin ice cover or the water surface will decrease the heat loss from the water to the atmosphere. One of the requirements of such an insulator is that it be lightweight so that substantial insulation thicknesses may be tolerated without overcoming the hydrostatic equilibrium of the ice sheet to an extent that would result in flooding of the sheet. If this were to happen, ice growth would be accelerated. The latter could be a problem if snow were to be used to insulate a thin ice cover and, because of this possibility, drifting snow should not be allowed to accumulate to such thicknesses in docking areas.

One possible method of insulating an ice cover is to use lightweight aqueous foams that would be deployed over the ice by means of spraying. These foams have been developed primarily for the agricultural industry and have been used successfully to prevent freezing of crops over a short period of time. Tests have also been conducted to determine the feasibility of using aqueous foams on ice and snow runways to prevent thawing. Grove et al (1963) carried out analytical and laboratory studies on the use of aqueous foams to prevent summer thawing of runways in Arctic regions. Foams were generated at -54°C. Later studies by Stahle (1964) at Point Barrow, Alaska, concluded that this foam was inadequate for long-term protection of ice and snow against summer deterioration.

This aqueous foam was used in tests by Dome Petroleum Limited to determine its application to the suppression of ice growth in the Arctic. Tests conducted at Resolute Bay in the winter of 1977 showed that the foam, while remaining intact despite fairly high winds, gradually collapsed over time and would require replenishing several times over the winter if ice growth were to be minimized. Snow accumulation also compressed the foam and caused the thin ice in the test area to become flooded. The cost of the foam in 1977, not including equipment and labour costs, was approximately $1.50/L.

The use of sulphur foams, which become rigid on application, to prevent thawing and settlement of roadways has been described by Ankers and Antoniades (1976). A test section of the Dempster highway near the MacKenzie delta was covered with the foam in August 1974, and the gravel roadway was installed on top of this foam. The foam, which was developed by Chevron Research Company and which had a density of 180 kg/W$^3$, thermal conductivity of 0.04 W/m -$^o$K, and compressive strength of 320 kPa, was found to be still effective 2 years after placement. In March 1977, a larger foam unit was tested successfully; however, no actual large-scale foam application has been carried out since then because of the lack of an economic market for the process.

Parfenov et al (1973) describes the use of a granular type of insulation to prevent ice formation around engineering structures. Experiments were conducted at the mouth of the N. Dvina River in the Soviet Union in the winter of 1970. They suggest that, when the insulation is no longer required, it is removed by an air ejection process and is stored for future use.

### 3.6 Floats and Pontoons

Depending on the ice control problem, techniques which incorporate structures in the berthing area could minimize ice buildup. For example, if the growth of the ice due to tidal effects is the primary concern, a sliding face on the dock support structure could move with the tides and, thereby, avoid the exposure of a layer of water to the atmosphere. The common ice collar or "bustle" would then be prevented from forming.

If the primary requirement is to minimize the ice buildup due to vessel traffic, a removable structure could be placed in the berthing area. An example of such a structure is the submersible pontoon shown in Figure 3-6. On approach of a vessel, the pontoon would be filled with water and sunk to the bottom. When the vessel departs, the water would be pumped out and the pontoon refloated. The pontoon would be hinged in order to guide its up and down movements. The top surface could be sloped so that any ice in the berthing area would be lifted by the pontoon and would slide to the outer edge of the berth. Insulation on the inside of the pontoon would prevent the water from freezing.

To avoid the problem of ice fog, which would hamper navigation during berthing, the pontoon would be submerged before the vessel reaches port so that a thin layer of ice will have had an opportunity to form in the berthing area.

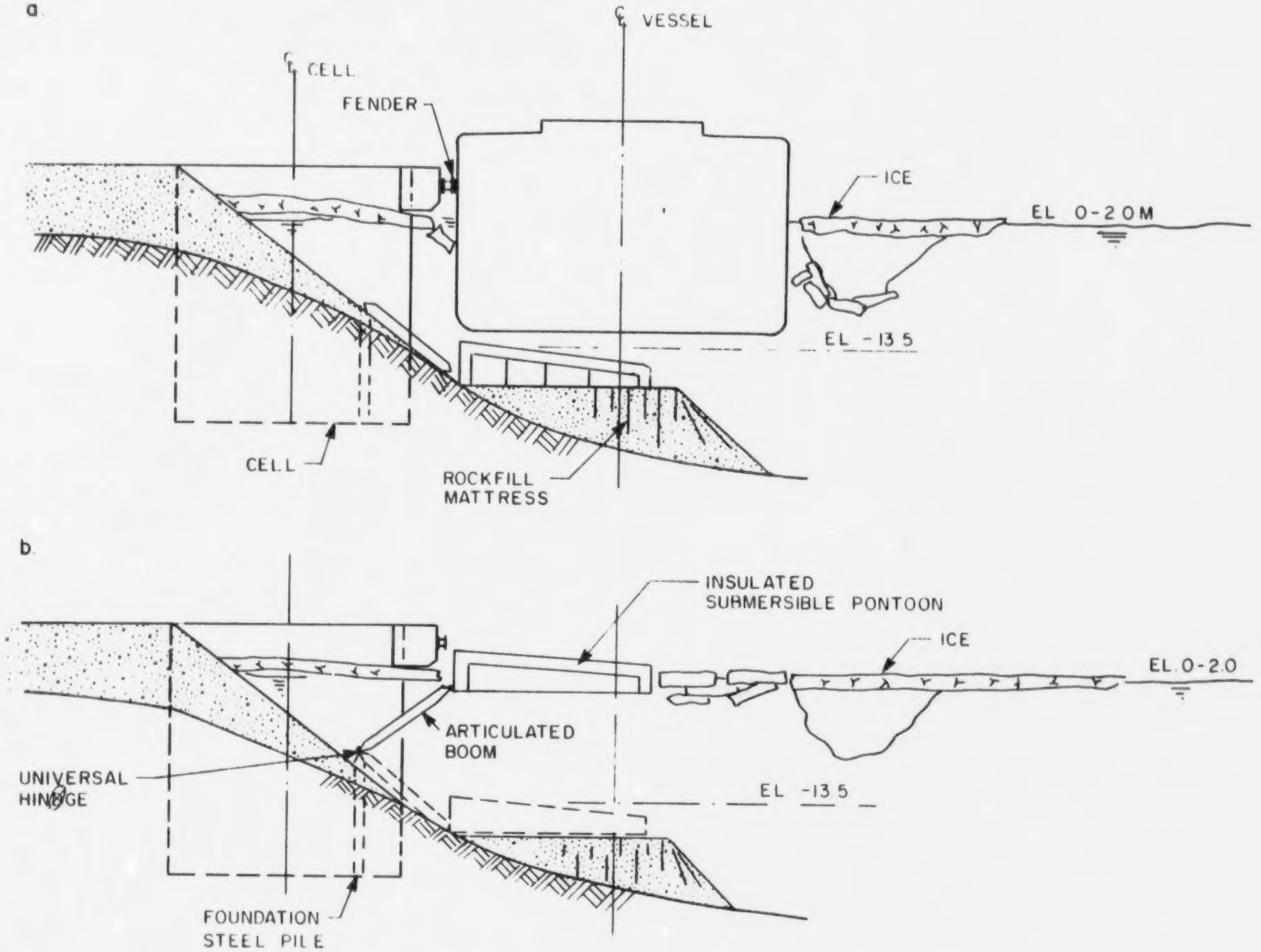

a.
℄ VESSEL
℄ CELL
FENDER
ICE
EL 0-2.0M
EL -13.5
CELL
ROCKFILL MATTRESS
b.
INSULATED SUBMERSIBLE PONTOON
ICE
EL.0-2.0
ARTICULATED BOOM
UNIVERSAL HINGE
EL -13.5
FOUNDATION STEEL PILE

FIG 3-6

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

SUBMERSIBLE PONTOON

ACRES

An important consideration arises in coping with the ice that would be pushed back into the berthing area by the departing vessel. It would probably be necessary to prevent most of this ice from entering the berthing area; otherwise, large amounts of ice would be eventually built up on the outer edge of the area. Additional systems could be implemented to prevent this. Such systems could consist of ice booms that allow the vessels to pass through, or surface propeller units, to repel the ice. Alternatively, it might be possible to stop the vessel immediately beyond the berthing area until the pontoon is raised.

There is no precedence for such an application to ice control and further investigation would be required to establish its feasibility.

### 3.7 Enclosures

Although it appears at first to be somewhat far-fetched, it may be technically feasible to enclose an entire berthing area. The air temperatures can then be maintained at above freezing levels to keep the berthing area free of ice without ice fog problems. This type of enclosure allows a controlled "inner climate" which will not only prevent the formation of ice in the basin, but also provide a more suitable working environment. A gross assessment of the heat losses can be expressed as follows.

$$H = H_v + H_c$$

$$= C_p \rho Q \ (T_i - T_o) + UA \ (T_i - T_o)$$

where

$H$ = heat input (kW)
$H_v$ = heat loss through ventilating air (kW)
$H_c$ = heat loss through conduction (kW)
$C_p$ = specific heat of air at constant pressure (kJ/kg-°C)
$\rho$ = density of air (kg/m$^3$)
$Q$ = flow of ventilation air (m$^3$/h)
$T_i - T_o$ = indoor-outdoor temperature difference
$U$ = insulating value of roof (kW/m°-°C)
$A$ = roof surface area (m$^2$)

In recent years, a great deal of research has been conducted into long-span structures. Tensile roof structures, in which structural members are loaded entirely in tension, have a clear advantage because of lower overall weight. The distances which can be spanned with these structures are theoretically much greater than any other kinds of construction. In general, unit construction costs are likely to be considerably less than conventional structures, especially for the longer spans.

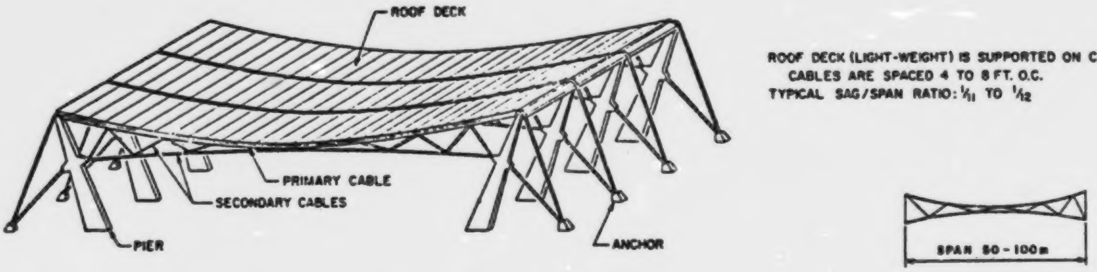
There are two basic forms of tension structures. The first is the air-supported structure, where a specially coated fabric roof is supported by an increase in air pressure in the building interior. The increased air pressure, only about 1/4 percent greater than atmospheric, is unnoticeable. A properly designed low-profile air-supported roof will result in negative pressure on most of its surface in very high winds which helps to maintain its shape. The current state-of-the-art is reflected in a multipurpose coliseum constructed at the University of Northern Iowa, a 16 000-$m^2$ structure, built in the shape of a semicircle about 150-m diam. The cost of the roof, including the supporting structure, was about \$130/$m^2$ in 1976 (Dupont, 1977). The largest structure built to date (The Pontiac Silverdome in Detroit) covers 42 000 $m^2$, spans 250 m, and weighs approximately 4.9 kg/$m^2$.

Air-supported structures depend on mechanical equipment for stability, which causes lower reliability and possibly lower safety. The trend in current construction is to rely more on the support of cables, masts or arches, which carry the loads from cable roof to the foundations.

The cable roof concept has been developed over several decades and several possible forms of this type of roof are shown in Figure 3-7. The most elementary structural suspension system is a catenary, similar to that used in suspension bridges. A flat roof enclosure can replace the roadbed as it is suspended from cables. This system requires end towers and abutments to resist the tension in the catenary; it also requires a stiff structure (e.g., the suspended roof) to eliminate the flutter in the cables and possible wind damage.

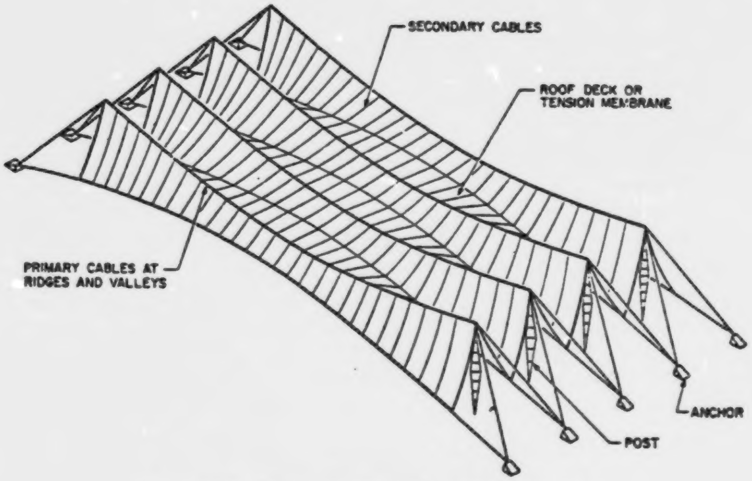
To avoid dynamic problems, without adding heavy weight to the structure, grids or interlacing cables have also been used. In some cases, these surfaces have opposite curvatures. Usually, the convex cables have an initial tension and press against the concave cables. In this way, the structure is damped and problems with vibration are minimized. The structure is then covered with a light roofing material. A number of cable roof structures of these types and others are described in a publication by Bethlehem Steel Co. (1968).

Low temperature steels for cables and masts have been developed for Arctic environments. The roof fabric must, of course, carry design loads for very low temperatures. The only fabric which has been accepted in the US under all code requirements for permanent building consists of a lightweight glass fibre coated with teflon fluorocarbon resin. This fabric is chemically inert, resists ultra-violet degradation and performs satisfactorily in Arctic temperatures. A


ROOF DECK
PRIMARY CABLE
SECONDARY CABLES
PIER
ANCHOR
SPAN 50 - 100m

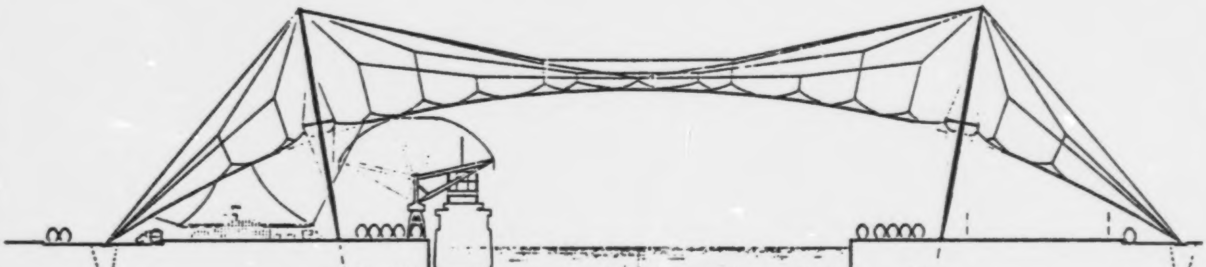
ROOF DECK (LIGHT-WEIGHT) IS SUPPORTED ON CABLES.
CABLES ARE SPACED 4 TO 8 FT. O.C.
TYPICAL SAG/SPAN RATIO: 1/11 TO 1/12

(a) CATENARY STRUCTURE


SECONDARY CABLES
ROOF DECK OR TENSION MEMBRANE
PRIMARY CABLES AT RIDGES AND VALLEYS
ANCHOR
POST

(b) DOUBLE CURVATURE STRUCTURE

FORMS OF CABLE ROOF STRUCTURES
(AFTER BETHLEHEM STEEL, 1968)



PROPOSED ENCLOSURE FOR BREMEN DOCK
(AFTER ROLAND, 1965)

FIG.3-7

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS
ENCLOSURE SYSTEMS

$700\text{-m}^2$ facility using this fabric has been constructed in Alaska, 160 km north of the Arctic Circle (Dupont, 1977).

The construction requirements will likely pose the greatest difficulty. The cable net, the membrane roof and supporting masts or arches can be preassembled off the site. The sheer size of the facility, however, may require heavy erection equipment and extensive on-site labour. The short construction season may result in severe logistics problems.

A study was completed in 1962 on the feasibility of enclosing an entire dock facility at Bremen, West Germany (Roland, 1965). The project was not completed, but the study results are of interest. In the Port of Bremen, the time lost due to weather conditions was approximately 10 percent. The task facing designers was to enclose a new dock basin approximately 1,600 m long and 150 m wide. The main benefits were the elimination of the transit sheds, savings on account of shorter quays, less expensive crane facilities and increased cargo handling productivity. The proposed design had nineteen 85-m masts over a span of 210 m. The roof membrane consisted of specially coated corrugated sheet-metal panels supported by a cable network to form an arch-like span, with headroom at quayside of 52.5 m. The total estimated cost of the structure (1962) was approximately $27 million. The reference does not state why the facility was not built.

# 4. ICE BREAKING

## 4.1 Conventional Icebreakers

Icebreakers are a specialized type of vessel specifically designed for the task of breaking ice. Their present state of development is the result of much study and analysis of bow and hull shapes, propulsion systems, and other devices all designed to produce the most efficient machine for the purpose intended.

In recent years, designs have incorporated bow shapes that maximize bending or shearing of the ice sheet and thereby, minimize larger resistance forces due to crushing. To reduce the friction of the ice along the midbody of the hull, bubbler systems have been installed to "lubricate" the hull with an air-induced spray. In some designs, the beam of the ship at the shoulders has also been increased to effectively cause a path to be broken which is wider than the parallel body beam, thereby minimizing ice contact along the midportion of the hull. Frictional resistance has also been reduced by the application of highly abrasion-resistant paints such as Inerta 160.

While any discussion of detailed icebreaker design is beyond the scope of the present work, some consideration may be given to overall powering requirements for certain ice conditions, while keeping in mind that the performance of any vessel depends on a host of interrelated factors.

This is illustrated by the work of Enkvist (1972) who suggested the following formula for the resistance experienced by vessels in a continuous uniform ice cover.

$$
\begin{aligned}
R_T = {} & C\frac{\sigma_f}{E}\;Bh\sigma_f(1+\mu_s\,\mu_c) \\
& + v^2B\tan^2\phi\;\rho_i(h+0.218\ell)(1+\mu_s\,\mu_c) \\
& + Blg\rho_w(0.167\ell\sin\Psi + 0.5H_{BW})\frac{(\eta_{\mu\Psi}+\eta_{\mu\theta})}{2} \\
& + g\rho_\Delta BhH(\eta_{sp}+\mu\eta_{s\mu E}\frac{L_E}{H})
\end{aligned}
$$

where

B = ship beam (m)
C = coefficient dependent on type of ice failure
E = strain modulus (MPa)
g = gravity constant (ns$^{-2}$)
H = ship draft (m)
h = ice thickness (m)

$H_{BW}$ = height of bow wave (m)
$L$ = ship length (m)
$L_E$ = length of entrance taken as 0.2 L (m)
$\ell$ = length of beam or width of broken cusp (m)
$R_T$ = resistance (tonnes)
$\bar{S}$ = average depth of submersion of ice (m)
$v$ = ship velocity ($ms^{-1}$)
$\alpha$ = half angle of entrance of a water line
$\beta$ = angle between section and vertical plane
$\phi$ = angle between stem and buttock and horizontal plane
$\Psi$ = angle between horizontal plane and a section perpendicular to water line

$\eta_{sp}$ = submersion ratio $^{=}f\ \bar{S}/H$
$\eta_{s\mu E}$ = friction form coefficient equals $\frac{A_{WLF}\mathrm{Sin}}{BL_E}$
$A_{WLF}$ = area of water plane of entrance ($m^2$)
$\eta_{\mu s}$ = friction form coefficient equals $1/\mathrm{Sin}\,\phi\ \mathrm{Cos}\,\Psi$
$\eta_{\mu c}$ = friction form coefficient equals $\mu/1 - \mu\frac{\mathrm{Sin}\,\phi}{\mathrm{Cos}\,\Psi}$
$\eta_{\mu\Psi}$ = friction form coefficient equals $\frac{\mathrm{Sin}\,\phi\mathrm{Cos}\,\psi + \mu\mathrm{Cos}\,2\,\phi}{\mathrm{Cos}\,\Psi\mathrm{Cos}\,\phi - \mu\mathrm{Sin}\,\phi\mathrm{Cos}\,\phi}$
$\mu$ = coefficient of friction
$\rho_i$ = density of ice ($kgm^{-3}$)
$\rho_w$ = density of water ($kgm^{-3}$)
$\rho_\Delta$ = density of water less density of ice ($kgm^{-3}$)
$\sigma_f$ = ice flexural strength (MPa).

This formula is one of many in the literature, but is probably less empirical than many others which tend to be limited in their application to vessels very similar or identical to that for which the formula was derived from either model or full-scale tests. Enkvist's formula, like others, is based on the premise that the resistance due to ice can be broken into three components. These are

-the resistance due to the actual breakup of the ice sheet

-the resistance due to submerging of the broken ice pieces

-the resistance which is related to the velocity of the ship and the frictional effects of the ice on the moving ship.

The limiting capability of a vessel is reached when the resistance provided by the ice is at the limit of the maximum net thrust available from the propellers or when

$R_T = T$

The maximum thrust may be expressed in terms of shaft power as

$$T_{max} = k_1 P_s$$

where

$k_1$ = thrust per unit power as determined by the characteristics of the propeller and hull. For unshrouded propellers, a range of 120 - 150 N/kw is suggested.

The net thrust is related to the maximum thrust by

$$T = k_2 T_{max}$$

where $k_2$ approaches unity as the vessel speed approaches zero.

Hence, the limiting resistance may be expressed as

$$R_T = k_1 k_2 P_s$$

For a vessel near bollard condition ($k_2 = 0.9$, say) and $k_1 = 120$ N/kw,

$$P_s = 0.0093\ R_T$$

Perhaps one of the simplest formulae for determining a rough estimate of vessel power in uniform ice of a given thickness is that due to Bustard (1973) who reviewed the power and dimensions of a number of icebreakers and suggested that the required power is a function of ship beam and ice thickness in the following manner

$$P = CBh^2$$

where

P = shaft power
B = vessel beam
h = ice thickness
C = constant = 527 $\frac{kW.}{m^3}$

For harbour icebreakers that are more or less continuously breaking ice to enable ships to dock, the resistance presented by the ice is that due not to a uniform ice cover, but to a matrix of blocks and pieces of ice that have been broken and redistributed possibly many times by the icebreaker. This ice can be much thicker than the undisturbed ice because of the repeated exposure of the track to the atmosphere. However, the straight line resistance experienced by the vessel operating in this ice could be less than that in the undisturbed ice because of its unconsolidated nature. This is a subject that requires further study to determine appropriate resistance relationships. Such ice is probably best represented as a cohesionless mass, or as heavy brash ice, whose resistance to vessel movement depends on the porosity of the matrix, the internal friction of the ice pieces, the depth of the ice and ship characteristics. Mellor [1980(a)] attempted to make some approximations for this resistance and for the power requirements of vessels in brash ice conditions.

The total resistance ($R_T$) experienced by the vessel is the sum of the bow resistance ($R_b$) and the frictional resistance aft of the bow ($R_f$). This may be written as

$$R_b = (1+2k_1\mu_e)BR$$

$$R_f = 2\mu_e k_2 BNR$$

where

$$k_1 = \frac{\text{Cot}\alpha}{2}$$

and $\alpha$ is a bow angle defined by the ship centerline and the secant from the stem to the shoulders

$\mu_e$ = effective friction coefficient
B = beam of the ship
N = constant equals 0.1
$R_2 = \acute{L}/B$ and $\acute{L}$ is afterbody length.

Hence,

$$R_T = (1+2k_1\mu_e)BR + 2\mu_e k_2 BNR$$

$$= [1+2\mu_e(k_1+k_2N)]BR$$

and

R = yield resistance of the ice

$$R = \frac{1}{2}\left(\frac{1+\text{Sin}\phi}{1-\text{Sin}\phi}\right)(1-n)\rho_i g\left(1-\frac{\rho_i}{\rho_w}\right)t^2$$

where

$\phi$ = friction angle, or angle of shear; experimental values of $\phi$ for brash ice range from 47 - 58 deg
n = porosity of ice mass
$\rho_i$ = density of the ice pieces
g = acceleration due to gravity
$\rho_w$ = density of water
t = depth of the ice.

The relationship developed above for shaft power as a function of resistance may then be used to determine the approximate power of the vessel for certain ice conditions. An example of the use of these relationships is shown in Figure 4-1 where the powering requirement of vessels for operation in uniform, undisturbed ice and in heavy brash ice are determined for various ship beams.

It can be seen that, as long as the ice is kept in an unconsolidated state, very large thicknesses can be negotiated. However, in the berthing area, such large volumes of ice could cause major berthing problems because ice would become jammed between the vessel and the dock. Ice control measures would then have to be implemented to prevent this.

### 4.2 Air Cushion Vehicles (ACV)

While the introduction of air cushion vehicles to movement over ice was brought about by the need to transport equipment in the north, in recent years, these vehicles have demonstrated their capability as ice-breaking platforms. This pertains particularly to their use in conjunction with a conventional icebreaker as a propulsion vessel; this combination has shown that the individual capability of the icebreaker alone can be increased dramatically by using it to propel an ACV. The ACV used in this manner is usually referred to as an Air Cushion Icebreaking Bow (ACIB), and much of the following discussion pertains to the experience gained in Canada with this ice-breaking technique.

#### 4.2.1 Ice-Breaking Mechanisms

ACV's break ice by one of two mechanisms, depending on the rate of movement of the vehicle.

The low speed ice-breaking mechanism is most effectively carried out by nonself-propelled vehicles. A high-speed self-propelled vehicle can also operate in this fashion but it is relatively inefficient. The principle involved is that the air pressure of the cushion depresses the water surface beneath the level of the bottom of the ice sheet and allows an air cavity to form. As the vehicle advances over the ice, the cavity moves with the vehicle, and the ice under the vehicle becomes, in effect, a cantilever beam which finally breaks due to its own weight. In order to form the cavity, the air cushion must depress the water level by at least the ice thickness plus a small amount to allow for ice bending. It is therefore simpler to express the air cushion pressure required for ice breaking as a pressure head equating 1 kPa to 10.2 cm of water. As a general rule, the ice thickness which may be broken is about 95 percent of the cushion pressure head.

In the high-speed ice-breaking mechanism, the ACV generates a wave train whose maximum height depends on the vehicle length. The train is characteristically a large bow wave forming a trough under the rear part of the vehicle and

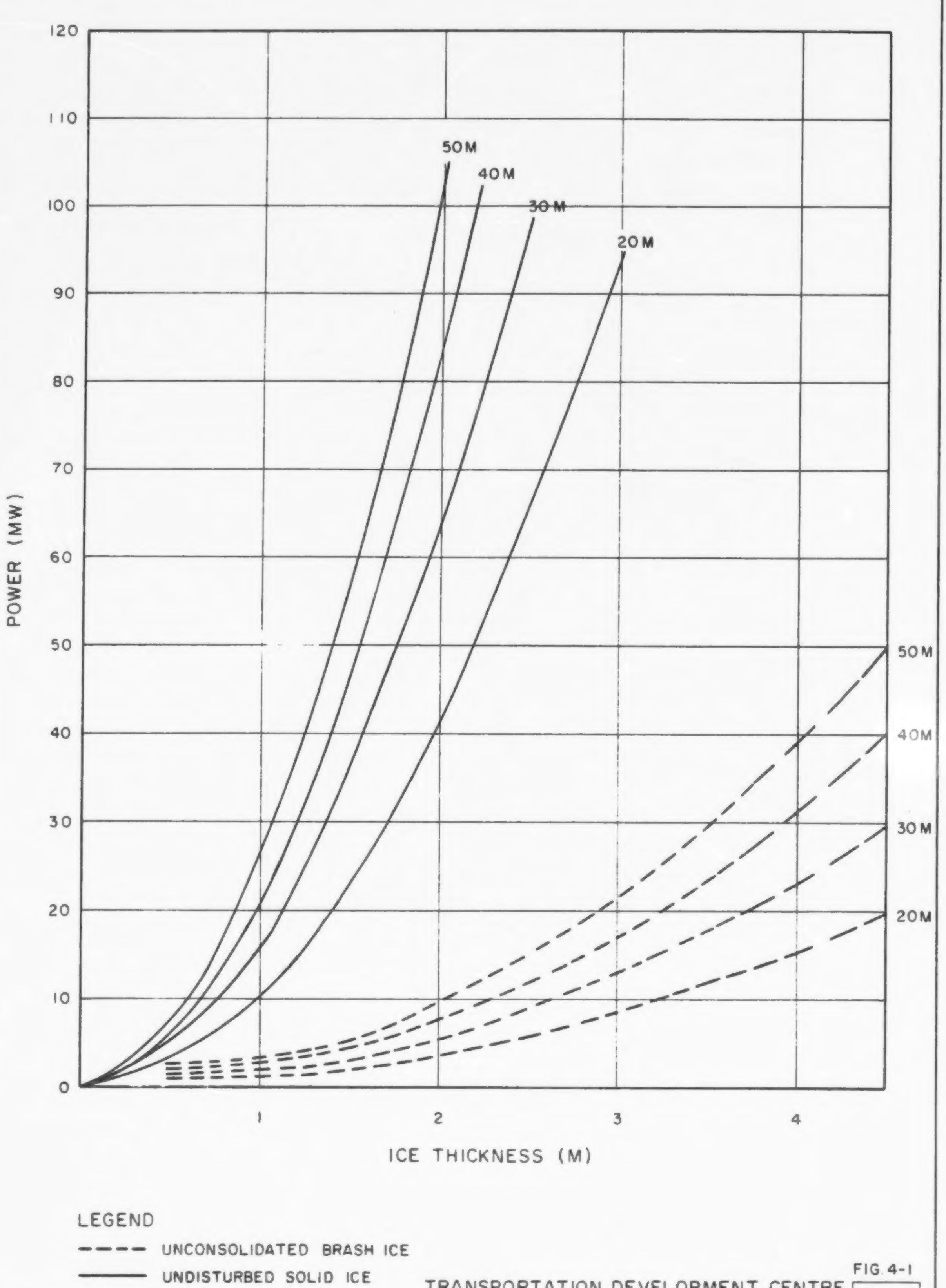


FIG. 4-1

APPROXIMATE POWER
REQUIREMENTS FOR SHIP MOVEMENT THROUGH SOLID AND BRASH ICE

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ACRES

a large amplitude wave about half the vehicle length at the stern. The influence of the wave extends some distance out from each side of the vehicle and the magnitude of the wave is intensified in water depths less than half of the vehicle's water line length. When an ACV operates over an ice sheet at a speed approximately equal to that at which the maximum waves are generated in free water, the ice surface behaves in a similar manner and it fails in bending. The limiting envelope of this mechanism is not known, but an ice thickness of 1 m has been broken continuously at speeds in the range of 19 - 48 km/h using a vehicle which generates maximum waves in ice free water at about 24 km/h.

Other air cushion, ice-breaking techniques involve manoeuvers at maximum wave-making speeds, such as rapid 180-deg turns. The waves can be intensified and directed against ice which is too thick or rough to be broken by the normal methods. Also, by rapid adjustment of propulsion power, the vehicle can change its pitch attitude causing abrupt changes to the load on the ice. The degree to which these manoeuvers can be carried out or be effective depends on the particular ACV and the controls which are available.

### 4.2.2 Precedence

The development of the ACIB has been exclusively a Canadian undertaking with model and full-scale testing having been conducted since the mid-1970's. A report by the Transportation Development Centre (1980), summarizes the program activities from 1975 to 1978, and presents recommendations for future programs (Hope et al, 1980). Prior to 1975, the Canadian Coast Guard (CCG) had carried out tests on a self-propelled ACV and model tests were undertaken in 1974.

During the winter of 1975/76, full-scale tests were carried out at Thunder Bay using the ACT-100 (Air Cushion Transporter), and the CCG icebreaker Alexander Henry as the propulsion vessel. The Alexander Henry has a shaft power of 2.5 MW and can break ice up to 30 cm thick in a continuous mode. In these tests, the ACIB/ship combination broke ice up to 74 cm thick.

Further tests were conducted in the winter of 1976/77 to investigate the ACIB performance when propelled by a number of different vessels and to test modifications made to the ACIB following the previous winter's program. Again, the results were very encouraging, and the following conclusions were drawn on the basis of the tests.

-The use of the ACIB to enhance the ice performance capability of commercial vessels of different characteristics is feasible.

-In order to have a track wide enough for continuous progress, and to alter course, the beam of the ACIB platform must be equal to, or greater than, the beam of the host ship.

-The effectiveness of the ACIB in breaking ice is a function of the cushion pressure and the physical characteristics of the ice. Hard, high-strength ice fails more readily than weak, soft ice of the same thickness, the latter requiring a reserve of higher cushion pressure to fail it completely.

-As a result of the increased speed of advance, the ACIB/ship combination was able to break a given area of ice more quickly than a ship alone. This resulted in significant fuel economies.

-A straighter and clearer track, than would result from an icebreaker alone, was produced with the ACIB/ship combination.

-Handling and manoeuvering of the icebreaker was improved to some degree. The ACIB platform appeared to stabilize the vessel and improve its' turning ability except in high winds and with high cushion pressure.

-Because of the difficulty in controlling the various parameters in full-scale testing, it was thought that model-scale tests should receive priority in attempting to formulate the theory of ice breaking with the ACIB/ship combination.

Since the full-scale tests of 1976/77, a number of model and analytical studies have been funded by Transport Canada to further advance the undertaking of ice breaking by ACIB's. While progress has been made in formulating mathematical models describing the ice fracturing and ACIB dynamics, these have not been validated by experimental data so that further scaled testing under controlled conditions appears to be warranted. The progress made to date has, however, been sufficient to allow for performance predictions within reasonable limits and, as a result, the CCG has designed and developed a new ACIB to operate on the Great Lakes. This craft was completed in March 1982 and underwent trials in Thunder Bay. As reported by Dubois (1982), the craft broke 0.8-m thick ice continuously at a speed of 0.5 m/s.

The ACT-100 underwent further testing during the winter of 1981/82 as a support vehicle to the oil industry operating on the north slope of Alaska. It was propelled by a 1.3-MW tug which independently can break 15 cm of ice. The combination of ACT-100 and tug was successful in breaking ice more than 60 cm thick during the tests.

In October 1978, another air cushion platform (HL-301) was used in Churchill Harbour in conjunction with a small harbour tug. While very little ice was present, the exercise demonstrated that the manoeuverability of the tug near the dock was not impaired, and had there been significant ice present, the performance of the tug would have been considerably improved.

Other studies are being conducted into modifications and additions to existing ice-breaking bows to incorporate air cushion features. Such a design described by Laframboise (1979) as the Advanced Icebreaker (AIB), would combine the best features of an icebreaker and an ACV to provide optimum performance.

### 4.3 Archimedean Screw Tractor (AST)

The AST which is a new craft in Canada has been developed by Mitsui Engineering and Shipbuilding Co., Ltd. of Japan and Arctec Canada Limited (Plate 4.1). As the name implies, its operating principle is quite old and is based on movement resulting from a rotating screw. In actual fact, the principle has been used in a similar craft in the Soviet Union for quite some time and a combination AST and rotary ice cutter are discussed in a later section of this report. At present, only a single prototype craft exists in Canada. The craft is amphibious with flotation provided by two screw pontoons which are driven by a conventional diesel power plant. Because the vehicle is amphibious, it is well suited to movement over broken ice covers and could have direct application in moving people and equipment over otherwise unsafe ice conditions. The vehicle can also negotiate rough terrain and highly deformed ice features.

While the most obvious application for the craft is as a work vehicle in difficult ice conditions, it is also capable of breaking ice. This is accomplished simply by riding over the ice sheet and bending the sheet using the weight of the vehicle. The thickness of the ice that can be broken clearly depends on the mass of the vehicle; the prototype craft, which weighs approximately 10 tonnes, can break ice of approximately 40-cm thickness. The broken ice then exists as large slabs which would have to be cleared from the track if resistance to a following vessel were to be minimized.

Ice trials of the prototype AST were carried out in Thunder Bay, Ontario, in March 1982, as part of a Transport Canada program to investigate a number of technologies that might be used to ensure an opening date for the harbour. During these tests, the AST demonstrated its ability to break ice and to move over the rough ice in a ship's track.

### 4.4 Mechanical Ice Cutting

Historically, various forms of mechanical ice cutting devices have been used to facilitate the removal of ice, and a number of cutting systems have been proposed for various

PLATE 4.1 ARCHIMEDEAN SCREW TRACTOR

applications. For example, it has been suggested that it would be useful to cut out cantilevers in the ice ahead of the bow of a vessel operating in ice. Designs have also been advanced for a rotating ring of horizontal ice cutters on an offshore column structure so that the ice is milled as it advances toward the structure. Chain saws, one of the most effective and simplest of ice cutters, have been used extensively in small-scale manual operations, and equipment such as ditching machines have been modified for use in ice. Large chain saws attached to driving vehicles have also been used to remove ice from lock walls.

Mellor [1980(b)] reviewed a number of ice-breaking concepts and made comparisons on the basis of energy requirements per volume cutting rate, which he called the specific energy of the device. This parameter may be used as the starting point in the design of an ice cutting machine; that is, once the desired volumetric cutting rate is known, the required power of the device can be estimated. While it might appear that any level of cutting performance could be achieved with a particular device given sufficient power, this is not the case since there is a practical limit to the useful power density of a cutting surface (power density is the power developed per unit area of the active cutting tool surface). Mellor suggests that the present power density limit for big rotary and belt machines is about 0.3 $MW/m^2$ while a realistic minimum value for the specific energy of a large cutting machine is 0.7 $MW/m^2$. Inappropriate design or improper operation could degrade these figures significantly.

### 4.4.1 Theoretical Considerations

#### Cutting System Requirements

The power requirements of an ice cutting system will be determined by four types of loads which are caused by the force required to

-cut the ice
-remove the ice chips from the cut slot
-pull the cutter tool through the water
-overcome tool--ice sliding friction.

The latter force may be neglected if the following requirements are met:

-the cutting tool does not bind in the slot

-the required depth of cut per revolution is less than the depth of the cutting teeth

-the cuttings are removed from the teeth and do not clog.

The power required to cut the ice is given by

$$P_c = \sigma_c t_s h v_a$$

where

$\sigma_c$ = unconfirmed compressive strength of the ice
$t_s$ = width of the cut slot
$h$ = ice thickness
$v_a$ = speed of advance of the cutting tool.

The power required to remove the cut chips is determined from the energy required to accelerate the chips up to the speed of the tool or

$$E = \frac{1}{2} m_c v_c{}^2$$

where

$v_c$ = speed of rotation of the tool
$m_c$ = mass of the cut chips.

Hence,

$$P = \dot{E} = \frac{1}{2} \rho_i t_s h v_a v_c{}^2$$

$$= 2\pi^2 \rho_i t_s h v_a r^2 \omega^2$$

where

$r$ = radius of cutter
$\omega$ = rotary speed of tool (rpm).

The power required to overcome hydrodynamic drag is

$$P_w = \text{Drag force} \times v_c \text{ X } N$$

$$= \frac{1}{2} \rho_w C_D v_c{}^2 A v_c N$$

$$= 4\pi^3 \rho \omega C_D l t_s r^3 \omega^3$$

where

$N$ = number of teeth in the water
$C_D$ = drag coefficient
$\rho_w$ = density of water
$A$ = area of the face of each tooth
$l$ = length of individual cutter.

## Propulsive Power Requirements

The power required to propel an ice cutting machine through ice is determined by the resistance forces experienced during forward motion. The total forward resistance may be written as

$$R_T = R_w + R_c + R_i$$

where

$R_w$ = resistance caused by water drag along the hull
$R_c$ = resistance caused by the ice cutter system
$R_i$ = resistance caused by breaking the ice and moving the broken ice pieces along the hull.

For a craft design similar to the mechanical ice cutter described in the following section, the hydrodynamic resistance is given by

$$R_w = 0.816 v_a^2$$

where

$v_a$ = the advance speed in m/s
R = resistance in tonnes.

The resistance of the cutter to forward motion is given by

$$R_c = C \frac{va}{w} \sigma_c t_s$$

where C = 0.1

and the resistance created by the ice is

$$R_i = 0.4 \rho_w gbhl$$

where

b and l = the width and length of the broken ice slabs.

The power required to propel the cutter at a speed $v_a$ with a thrust equal to the total resistance and efficiency $\eta$ is

$$P = \frac{R_T v_a}{\eta}$$

and the total power requirement is the sum of the propulsion power and the cutting power.

### 4.4.2 Precedence

A mechanical ice cutter (MIC) developed by Arctec Inc., Columbia, Maryland, is a self-propelled waterborne craft having three electrically-driven rotary saws across its bow (LeCourt, 1973). The hull design is such that the cut ice passes down and under the hull, then under the ice on either side of the cutter by the passive deflection of underwater skegs, thus creating an ice free track.

Tests done on a 1/6 scale model of the MIC in river ice in the northern United States have showed that the cutter would be an effective and efficient means of ice control. The full-scale ice cutter was intended to clear a 12-m wide channel in 0.6 m of ice while travelling at 9 km/h. Lewis (1973) calculated that a MIC using a conventional propulsion system requires 70 percent of the energy requirements of a conventional ice-breaking vessel of the same beam; he also maintains that the cutter would be considerably more effective than an icebreaker since it would provide an ice free channel (which, however, would presumably become more congested with subsequent cuttings since the ability to displace ice sideways would be gradually impaired as ice pushed underneath the undisturbed ice builds up).

An article in a Soviet journal describes an ice cutter used to facilitate ice movement on a river in Russia (Koren'kov, et al, 1975). The saw was a single-bladed circular type, 2-m diam and was mounted on an amphibious craft propelled by two screws in a manner similar to the AST described previously. The particular unit described was used in 1972, 1973 and 1974 to cut criss-cross slots in river ice. Tests were carried out in temperatures near 0°C and in ice varying in thickness from 0.7 - 1.2 m with 0.10 - 0.15 m of snow. The total power of the device was 85 kW which enabled it to cut ice at rates of up to 0.25 km/h. The rate was impaired somewhat by the snow cover. The width of the slot cut in the ice was 0.15 m.

The use of large chain saws to remove ice from lock walls is described by Garfield, et al (1976). Tests were conducted with a coal saw and a lumber saw attached to ditching tractors to remove ice from the walls of a lock at Sault Ste. Marie, Michigan. The coal saw was 4.9 m long and was able to travel through ice 1.2 - 1.8 m thick at a rate of 3 m/min and through ice 2.1 - 2.4 m thick at 2 m/min. The lumber saw was 4.4 m long and cut through ice 1.5 - 1.8 m thick at a rate of 0.6 - 0.9 m/min.

### 4.5 Ice Breaking with Explosives

The use of explosives to enable ships to move in heavy ice conditions and to remove ice jams in rivers is quite old. Frankenstein and Smith (1970) report that the use of explosives for destroying jams goes back to 1758. The early use of explosives in ice work in Canada has been reported by Barnes (1928) who used thermit as the destructive agent.

During the 1960's, Frankenstein and Smith report that the US Army effectively used a newly developed explosive, Ammonium Nitrate Fuel Oil (ANFO), to remove ice jams. It was found that the best results were obtained when the charge was placed at a distance below the ice surface which varied as the cube root of the charge weight and that the resulting hole diameter depended on the charge weight in a similar manner. The most efficient method for the removal of river ice jams was to place between 10 and 20 charges under the ice and detonate them simultaneously, the spacing of the charges being 1-hole diam. In this manner, more than a mile of river ice could be broken up in an 8-h period.

Further study on the use of explosives for breaking ice has been reported by Goode and Teller (1971). They suggest that when attempting to break ice over a large area, it is necessary to obtain displacement of the total cover at the same time, and this can only be obtained if the charge is placed in the water beneath the ice cover. The experimental data suggested that the charge be placed twice the distance into the water as the thickness of the ice and that the charge weight (in pounds) be numerically equal to twice the distance of the charge from the top surface of the ice (in feet). They caution that allowances must be made for different circumstances, and note that it is unlikely that ice formations which are thicker than about 5 m can be broken and scattered with a subsurface charge. For massive formations, it is suggested that standard drilling and blasting be used. It is concluded that, with the use of explosives and fail-safe techniques, ports and shipping lanes which are now closed to traffic could be kept open for longer periods. One method of doing this would be to deploy "sleeper" charges in critical areas during the open water season and detonate them as required during excessive ice conditions.

Mellor [1980(b)] reports on the use of compressed gases and propellents to break ice. Two commercial gas-blasting systems have been tested for ice breaking. These are the Airdox system, in which air is compressed to 83 MPa and then discharged abruptly, and the Cardox system, in which liquid carbon dioxide is abruptly vapourized by an electric heating element and discharged at high pressure. The volume of gas released in a single discharge is limited for both systems and, therefore, there is a limit to the thickness of ice that can be broken (about 0.6 m).

Another approach to gas blasting is based on special devices that ignite fuel/air mixtures. One such device was designed specifically for breaking floating ice. It had a 0.14-$m^3$ combustion chamber that was charged with a mixture of propane and compressed air to pressures in the range 0.40 - 0.65 MPa. The venting port of the combustion chamber was slid beneath the ice, the mixture was ignited by a spark plug, and as the chamber pressure increased by a factor of 6, the gas was discharged. For an initial charge pressure of 0.55 MPa, the potential energy of the blast was approximately $1.7 \times 10^6$ J, which is about the same as energy of standard Airdox and Cardox shells. However, the fuel/air combustion device was less effective than the high pressure systems, reaching the limit of its capability with 0.3 m of ice.

Mellor [1980(b)] points out that the fuel/oxidant combustion system has a number of attractive features for repetitive blasting, and with more careful design, it could be made to break thick ice. Design calculations should take into account the combustion process, the behaviour of gas bubbles in water, the bearing strength of ice plates, and the inertial response of ice plates.

In an attempt to further determine relationships between charge size, placement and crater size, and to corroborate data from Mellor (1972), Fonstad et al (1981) carried out a number of tests on Drummond Lake in British Columbia. They arrived at the following formulae:

$w = 24.8\ h^3$
$d = 0.388\ h$
$R = 7.96\ h$

where

w = weight of the charge in kilograms
h = ice thickness in metres
d = depth of the charge below the ice in metres
R = radius of the resulting crater in metres.

These relationships differ significantly from the "rules-of-thumb" suggested by Goode and Teller (1971), but arise from a detailed regression analysis by Mellor on all previously available data together with an analysis of the data collected during this particular program.

### 4.6 Thermal Ice Cutting

Over the years, experimentation has taken place on the use of thermal sources, usually steam or hot water, to facilitate ice-breaking. The general objective has been to make narrow cuts in ice to minimize the otherwise prohibitive amounts of energy required to melt ice over a wide area, for example, a ship's beam. Research in this area has been described by a number of writers (Peschanskiy, 1967; Legerer, 1973). In a more recent article [Mellor, 1980(b)], it is suggested that the main concern with such systems is the achievement of a sufficiently high penetration rate, the rate of melting at the ice surface being limited to the attainable power density and the heat transfer process.

If u is the penetration rate (m/s), Q is the power density ($MW/m^2$) and $E_s$ the specific energy ($MJ/m^3$) required for melting, then

$$u = Q/E_s$$

For typical sea ice with $E_s = 290\ MJ/m^3$, the power density requirement to achieve a penetration rate of 0.01 m/s would be about 3 $MW/m^2$ at 100 percent efficiency. If the rate of cutting in the horizontal direction is to be much higher than this rate, then the cutter has to have a very long active surface which would result in fairly high power requirements.

### 4.7 Cutting with High-Pressure Water Jets

The most recent report on research carried out on the use of high pressure water jets is due to Coveney (1981), who has described work carried out since 1977 by the National Research Council of Canada in Ottawa. Tests were conducted in freshwater and simulated sea ice. Results were generalized and a regression analysis resulted in the following equation for freshwater ice

$$y = 0.7 + \frac{0.29\ Pe^{T_i/20}}{\sqrt{u}\ s^{1/6}}$$

where

$T_i$ = estimated ice temperature (°C)
P = system power (kW)
u = nozzle traverse speed (km/h)
s = average nozzle stand-off distance (cm)
y = average penetration (cm)

The penetration capability depends significantly on the ice strength which is accommodated by the inclusion of ice temperature in the equations. For freshwater ice at 0°C, a power input of 4 MW at a traverse speed of 5.5 km/h could cut about 3 m of ice. At an ice temperature of -20°C, this penetration depth reduces to about 1.5 m.

Pressures used in the tests ranged from 4 - 73 MPa with a minimum pressure of 40 MPa being required to produce a clean cut in the ice.

Earlier work on the use of high pressure jets has been presented by Mellor (1974). Small-scale tests were conducted with nozzle pressures up to 690 MPa. From this research, preliminary design calculations were made for simple jet devices to be used as

-aids for icebreakers
-cutters for slicing a channel through sea ice
-protective cutters for marine structures.

Tests have also been conducted with high-pressure water jets to determine their effectiveness in deicing walls in the St. Lawrence Seaway Authority locks. It was concluded that the method was too expensive for the effects achieved and no further tests were conducted.

### 4.8 Cutting with Lasers

Mellor [1980(b)] considers briefly the application of lasers to ice cutting and points out that, while lasers can transmit radiant energy over long distances through air and can develop very high power density in the target area, once the laser beam impinges on the ice, it is likely to act simply as a melting device and be subject to the usual limitations. Limited test data on a $CO_2$ laser indicated that a specific energy of 414 $MN/m^2$ is required for the cutting of freshwater ice. To cut a slot 5 mm wide and 2 m deep at a traverse speed of 1.5 m/s would require a laser power of 6.4 MW with this specific energy.

### 4.9 Cutting with Chemicals

Parsons and Hopkins (1977) have described a method for ice destruction in which ice is reacted with gases such as ammonia, hydrogen chloride or sulphur dioxide. The gaseous chemical is passed through a nozzle and impinges on the ice. In tests with ammonia passing through nozzles of a few millimetres diameter, penetration rates in the order of 1.5 m/min were obtained at flow rates of 75 L/min. The authors suggest several applications of the concept, ranging from iceberg destruction to weakening ice in front of a ship. Development work is continuing on the technique.

Chemical sprays have also been tested for deicing lock walls; tests carried out by the St. Lawrence Seaway Authority achieved only limited success and the method was abandoned.

## 5. ICE REMOVAL AND DISPOSAL

A number of possible techniques may be addressed for the removal and disposal of ice in critical ice control areas. Depending on the technique, these might be implemented when ice conditions become unmanageable for vessels in a terminal area. The conditions to be dealt with may range from loose brash ice that has been broken from several transits of vessels to relatively large ice pieces that have been broken from a consolidated ice cover.

The basic removal techniques presented here are

-lifting
-towing or pushing
-conveyors and slurry pipelines.

### 5.1 Removal by Lifting

The energy requirements associated with physically removing ice may be estimated. The minimum specific energy required for slow lifting of a block of ice to height H, neglecting water resistance, acceleration effects and the efficiency of the lifting mechanism, may be written as

$$E_s = \rho_i gH$$

For an ice block with $\rho_i = 0.9$ kgm/m$^3$, the minimum specific energy to lift it to a height of 3 m is 26 kJ/m$^3$. Added to this minimum specific energy, one must consider energy expenditures to prepare the ice for removal and to transport the ice away from the control zone. This specific energy may be compared with thermal cutting (melting) at a value of 290 MJ/m$^3$ and mechanical cutting at 2 MJ/m$^3$. By multiplying the desired volumetric removal rate by the specific energy, the required power may be determined. This value would represent the minimum requirement; inefficiencies in the overall ice control system could cause very considerable increases in the final power requirement. In an actual design, logistics and practical considerations may quickly determine the feasibility of the technique even though power requirements may appear reasonable.

### 5.2 Towing and Pushing

For large ice pieces broken by a vehicle such as an ACV or an AST in a terminal area, it is possible that a towline could be passed around the floe which would then be pulled away from the ice control area by a support vehicle such as an ice-breaking tug or an AST. Alternatively, a plough-shaped attachment to the work vehicle could be used to push the ice away from the ice control zone. Ice pieces broken by a tug would probably be too varied and in many cases too small for towing of individual floes although it might be possible to employ a tow mechanism that could constrain a conglomerate of ice pieces. A pushing mechanism might be more attractive for such an operation however.

The specific energy required to push a slab of length a distance d at a speed u along the water surface is given by Mellor et al (1978) as

$$E_s = \rho_w u^2 \ (d/\ell)$$

For a pushing speed of 0.5 m/s and distance of d = 100 $\ell$ the specific energy requirement is 26.6 kJ/m$^3$.

For the case of an ice slab being removed from the ice control zone by submerging it, the specific energy requirement can be determined from a consideration of buoyant and hydrodynamic drag forces. If a flat slab is pushed down into the water without appreciable tilting, the resistance due to buoyancy is

$$R_1 = h \ (\rho_w - \rho_i) \ gA$$

where

h = the ice slab thickness
A = ice slab area.

The hydrodynamic drag at constant speed of submergence u is written as

$$R_2 = \frac{1}{2} \rho_w \ u^2 \ C_d A$$

where $C_d$ is a drag coefficient.

To push the slab through a vertical distance $h'$, the specific energy requirement is

$$E_s = h' \ (\rho_w - \rho_i) \ g + \frac{1}{2} \rho_w u^2 \ C_d \ \frac{h'}{h}$$

For a submergence depth of 3 times the ice thickness of 1 m, and a steady submergence speed of 0.5 m/s with a drag coefficient of 1.5, the specific energy is 3.5 kJ/m$^3$. This value does not include the acceleration affect which could be substantial if the ice were thrust down abruptly.

### 5.3 Conveyors and Slurry Pipelines

The use of conveyors or pipelines would be a transfer of standard technology used in less severe climates for the movement of diverse materials, but for the present application, the experience with moving coal or ore is probably most appropriate. One suggestion for removing and disposing of brash ice is the use of a self-propelled bucket wheel and boom conveyor system (Arctec Inc., 1979). Ice is scooped up by the continuously rotating bucket wheel and transferred by conveyors to a boom which reaches to the disposal area (the undisturbed ice or shore). One might envisage such an arrangement being attached to an AST.

Some investigations have been undertaken on the use of slurry pipelines to remove and dispose of ice. Vance (1980) reports that laboratory studies indicate that a slurry concentration greater than 50 percent ice could cause freeze-up problems in the slurry pumping mechanism and peripheral freezing of the slurry pipeline which would decrease the effective pipe diameter. This potential freezing problem could be reduced by keeping the slurry concentration below 50 percent or by introducing a heating system for the pump and pipeline. Presumably, such problems would be lessened as well, or even eliminated, by submerging the pipeline.

A further consideration is the size constraint on the ice pieces. The ice must be reduced in size so that it can fit through the slurry pump and pipeline. While the pipeline can accommodate solid ice about 1/4 - 1/2 the pipe diameter, the pump will require much smaller pieces. Vance estimates that the ice pieces will have to be reduced to 5 - 7 cm which clearly will require the use of a crusher to prepare the ice before slurrying.

An estimate of the pumping requirements for slurrying ice may be made by referring to relationships derived for slurrying of coal. The slurry volume and velocity are related to the pipe diameter by

$$D = 1.15\sqrt{\frac{Q}{v}}$$

where

$D$ = pipe diameter (m)
$Q$ = volume rate of slurry flow ($m^3/s$)
$v$ = flow velocity (m/s).

The volume flow rate is determined by the ice volume to be removed which in turn depends on the temperature regime at the site and the maximum thickness that can be tolerated in the ice control zone. Slurry velocities are limited to the minimum velocity required to prevent settling of the ice and to the maximum velocity needed to prevent excessive friction head losses. Such losses together with the desired discharge pressure, will determine the required pumping power. In terms of specific energy requirements, Mellor et al (1978) estimate that to pump an ice slurry a distance of 300 m at a speed of 9 $m^3/s$ would entail a specific energy of 4 $MJ/m^3$; for a pumping distance of 1 km, the requirement would be 13 MJ/$m^3$. These estimates are based on data for the transport of rocks and coal which suggest that moderately high concentrations could be pumped for energy expenditures of less than 4.2 kWh/t-km.

# 6. ICE DIVERSION

Techniques which may be employed to divert ice away from dock structures have their principle applications in areas exposed to moving ice, such as river ports or those which may be affected by floe ice. Since the majority of Canadian Arctic ports will present ice problems associated with fast ice, such diversionary techniques will have only limited application, although it is clear that during freeze-up and breakup periods, ice movements might be controlled at such ports by diverting the ice away from critical berthing areas. In addition, diversion techniques may be used in combination with other ice control methods to move broken ice away from the dock. In general, three techniques may be considered. These are booms, artificial structures and flow developers.

## 6.1 Booms

Booms have been used primarily for the control of river ice and mainly for the purposes of preventing ice intake to power plants rather than the prevention of ice interference with port and harbour structures. There is considerable discussion in the literature on the installation of a number of booms on the St. Lawrence Seaway system. A recent study by Lewis and Johnson (1980) focused on the use of booms on a portion of the Seaway to allow the safe transit of vessels while minimizing the movement of ice downstream and maintaining a stable ice cover. Navigation channels were maintained by using booms with gaps to allow ship movement. Such an installation on the St. Mary's River connecting Lake Superior and Lake Huron has proved to be successful (Perham, 1977).

The tension in the boom cables connecting the boom elements is given by Perham (1974) as

$$T = \frac{xF_D}{\cos\Theta\ [4(\frac{s}{x})^2-1]^{1/2}}$$

where

$x$ = one half the cable span
$s$ = boom cable length
$F_D$ = total drag force per unit length on the boom due to water and ice
$\Theta$ = boom cable angle.

The total force on the boom is the sum of the following forces:

-the hydrodynamic force at the upstream edge of the ice cover
-the frictional drag of the water flowing under the ice and the air above
-downstream component of the weight of the ice cover
-impact force of collecting ice floes
-frictional force from the shore line.

Parfenov et al (1973) describe the use of floating booms to prevent broken ice from entering berthing areas. One such design forms an adjustable barrier consisting of a series of floats which is pressed together forming a barrier when broken ice is driven against it. As a ship passes through the barrier, the floats located directly in front of the hull are parted and form compact accumulations of ice to the sides. After the ship has passed through, the floats return to their initial positions. There is no indication in the literature as to whether there are any such installations of this design however.

Tsang (1981) describes a finned boom that was developed for the purpose of recovering oil in ice-infested rivers. Model studies in synthetic ice indicate that such a boom could be used in harbours to allow passage by vessels while still retaining the broken ice pieces. Consideration might be given to the use of such booms in a harbour to prevent ice broken by an exiting vessel from floating back into the area in front of the dock. This would minimize the ice buildup in front of the dock since the majority of the ice in that area is pushed there by vessels as they depart the dock.

### 6.2 Structures

In some areas, it might be feasible to consider the use of structures such as artificial islands, breakwaters and berms to modify ice movement in an ice control zone. Such structures would be strategically located to prevent the impact of ice on the dock facilities by immobilizing the ice or by diverting it away from the control area. Such structures might also be used in conjunction with other ice control techniques to provide an overall control system. An example would be the use of a berm serving as an enclosure for a thermal discharge system while at the same time preventing the ice beyond the control zone from impacting on the activities or structures in the control area.

Again, to date, the application of such ice control methods has been almost totally limited to river ice. Artificial islands have been constructed in the St. Lawrence River to stabilize the ice cover and prevent jams and flooding (Danys, 1979). At a petroleum terminal opposite Quebec City, 3 sheet-pile cells are located at the upstream end of the wharf in a line at right angles to the berth to stop the ice and deflect it toward the center of the river (Dery, 1981). An ice deflector is also used at a ferry landing wharf at Levis, again near Quebec City. This deflector consists of a concrete box filled with rock and causes ice moving downstream to be deflected past the berth area with minimum restriction.

A recent application of a protective structure in the arctic is the use by Dome Petroleum Limited of a dredged berm to protect a fleet of drill ships in their winter mooring basin in McKinley Bay. The berm is meant to prevent landfast ice movements due to west and northwest winds from impacting the fleet. Such a structure was deemed to be necessary following substantial ice movements in McKinley Bay in December 1979.

In recent years, designs for offshore arctic petroleum production and loading terminals have focused on the use of artificial islands or underwater berms supporting concrete or steel caissons to provide a protected "harbour" enclosure. These structures would provide protection from the moving pack ice but would still require some form of ice management inside the enclosure area in a manner similar to other dock facilities that are operated in fast ice conditions. The forerunner of these offshore harbours is Dome Petroleum Limited Tarsiut exploratory island in the Beaufort Sea. This structure, which consists of caissons resting on a submerged berm, is actually filled inside to provide the necessary platform for drilling operations. The concept, however, can be extended to a terminal facility which will allow tankers to dock inside the enclosure. Such a concept has been put forth by Dome Petroleum Limited in the form of their Arctic Production and Loading Basin (APLB). Again, such a structure will provide protection from external ice forces, but will present problems of ice control inside the enclosure which will be similar to those of conventional harbours.

### 6.3 - Flow Developers

In a broken ice regime, flow developers might also be used to move or direct ice away from dock structures. Flow developers could take the form of a standard air bubbler, an air cannon mixer ("burper"), wave generator or propeller system.

Air bubbling units are used as pneumatic barriers by the St. Lawrence Seaway Authority to prevent ice from entering the locks where it gets crushed against the dock walls by ships passing through (Poe, 1982). An extension of this application would be as a barrier to prevent broken ice from moving into the berthing area in front of a dock as a vessel exits. This would minimize the buildup of ice in the berthing area and would facilitate berthing.

An indication of the power required to counteract the moving ice in the latter application can be obtained by considering the drag forces on the ice pieces due to the surface water movement as the vessel departs. The force due to the water drag can be written as

$$F_D = C_D \rho A v^2$$

where

$C_D$ = drag coefficient
$\rho$ = water density
$A$ = surface area of ice in contact with water
$v$ = speed of ice.

If a propeller is used in a horizontal mode at the water surface to prevent the ice from moving into the berthing area, the thrust from the propeller must equal the drag force on the ice. The forward thrust from a propeller is given by

$$F_p = C_p \rho \omega^2 D^4$$

where

$C_p$ = constant which depends on propeller shape, Reynolds number and the advance ratio (J), where $J = V/ D$ and V is the advance velocity. For a stationary propeller, $V = 0$ and $J = 0$.
$\omega$ = rotational speed of the propeller
$D$ = propeller diameter.

By equating the two forces, the propeller diameter can be expressed in terms of the other parameters as

$$D = \left[\frac{C_D}{C_p} \frac{Av^2}{\omega^2}\right]^{1/4}$$

The propeller power is given by

$$P = C_p \rho \omega^3 D^5$$

Hence,

$$P = C_p^{1/4} C_D^{5/4} \rho \omega^{1/2} A^{5/4} v^{5/2}$$

and for a specified area and movement of ice and typical propeller dimensions, the propeller power required to resist the ice movement can be determined.

Propellers could also be used behind docks, where the design allows, to push ice to the rear thereby creating a low resistance zone into which ice could be pushed by a berthing ship. This could be quite feasible with an open-face dock which is a sufficient distance from shore to allow for displacement of the ice.

# 7. TECHNIQUE EVALUATION

In evaluating the ice control techniques presented in previous sections, a number of broad criteria were established. These criteria refer to such parameters as overall effectiveness, energy requirements, reliability, costs, precedence, operational safety, construction aspects, port operations and environmental effects. The following questions were considered in this evaluation.

-Is the required system effectiveness attainable?

-For the required effectiveness, is the system size practical?

-Are the system installation or construction procedures within reason?

-Is the required energy source or supply for system operation presently available or will it be available in the short to midterm future?

-Is the energy requirement within reason?

-Are the system material requirements available under present technology?

-Is the impact on the environment acceptable under present technology?

-Is the system operational under arctic conditions?

-Is the system operation within acceptable human safety limitations?

-Are the system costs within reason, and are development costs within practical limitations?

-Have precedents been established for system performance and reliability?

Table 7.1 summarizes the general evaluation of the techniques. The following sections discuss the evaluation in more detail.

## 7.1 Ice Suppression

### 7.1.1 Thermal Discharge

The use of thermal discharge systems to control ice in harbours is generally feasible only if a degree of enclosure is maintained to allow a heat reserve to be built up. It is conceivable that, given enormous quantities of energy and a

**TABLE 7.1**

**GENERAL EVALUATION OF ICE CONTROL TECHNIQUES**

| | Evaluation Consideration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Effectiveness** | **Capital Cost** | **Construction** | **Precedence** | **Reliability** | **Safety** | **Environmental Effects** | **Operational Power Requirement** | **Application to Study Ports/Harbours** |
| **1 - ICE SUPPRESSION** | | | | | | | | | |
| 1.1 - Thermal Discharge | Horizontal discharge effective only if area is enclosed.<br>Vertical discharge directly under ice cover effective without enclosure. | Depends on size of ice control area, but in low cost category. | Fabrication can be done in temperate climate; assembly on site; straightforward construction. | No full-scale diffuser system in place; several single "nozzle" outflows from industrial installations; documented experiments and lab studies. | Should be very reliable. | No safety problems other than ice fog if power input is too high. | May be small effect due to slight warming of water and entrainment of organisms in intake water. | Very low if waste heat, otherwise, low to very high depending on operational requirements. | From present usage and knowledge of future use, only location for waste thermal discharge is Bridport Inlet.<br>For vertical discharge (with or without waste heat), all ports/harbours are possible candidates. |
| 1.2 - Bubblers | | | | | | | | | |
| (a) Continuous | Effective in areas with thermal stratification; usually freshwater or large river deltas where warm saline water is overlain by freshwater; may be used with thermal discharge. | Very low cost for average installation near docks. | Easily constructed; best to install before freeze-up; need to accommodate propeller wash and anchors. | Numerous successful installations in Great Lakes; also at Tuktoyaktuk. | Very reliable. | No safety problems; possible ice fog. | No negative environmental effects. | Very low. | Bubblers generally only applicable to Great Lakes ports; may also have possibilities in Tuktoyaktuk, McKinley Bay and NW Point, Lake Melville; could be used in Arctic in conjunction with freshwater from nearby lakes. |
| (b) Air Cannon Mixers | Effective in areas with thermal stratification; may also have some effect in isothermal water due to surface turbulence; horizontal surface velocities less than with continuous bubblers. | Low cost. | No construction problems; assembly onsite; need to accommodate propeller wash and anchors. | Installation at Thunder Bay, March 1982. | Very reliable. | No safety problems. | No negative environmental effects. | Very low. | Same as with continuous bubblers. |

Table 7.1
General Evaluation of
Ice Control Techniques - 2

| | Evaluation Consideration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Effectiveness | Capital Cost | Construction | Precedence | Reliability | Safety | Environmental Effects | Operational Power Requirement | Application to Study Ports/Harbours |
| 1.3 - Wave-Making Devices | Not proven in full-scale; lab and small-scale studies encouraging.<br>Creates large quantities of frazil ice. | Depends on size of installation; low cost. | No construction problems; can be prefabricated off-site. | Small-scale studies; installation in Frederikshavn, Denmark. | Should be reliable. | Possible continuous ice fog. | No negative environmental effects. | Very low. | Need further testing to determine applicability; not feasible year-round in Arctic locations because of distance from open sea or moving pack. |
| 1.4 - Enclosures | Very effective in limiting ice growth. | High cost. | Problems due to equipment required, short construction season in the Arctic, foundation and entry and exit of vessel. | Numerous examples of such structures built over land in temperate climates, none built over water. | Uncertain in an Arctic environment. | May be safety problems depending on port operations. | Could have beneficial effect on overall harbour environment. | High due to heat loss. | Has universal possibilities although at present does not appear feasible; more appropriate in sheltered harbours with fast ice and low tidal effects. |
| 1.5 - Dusting | Limited effectiveness; very sensitive to weather conditions. | Low cost. | No construction involved. | Several incidents in Canada, Alaska and USSR. | Not very reliable. | No safety problems. | May have detrimental effects depending on dust type. | Very low. | Limited use in seasonal harbour during breakup; otherwise, can be dismissed. |
| 1.6 - Insulation (rigid or foam) | Very effective in limiting ice growth. | Low cost. | Little construction involved; application problems. | Small-scale use of insulation on water surface; no large-scale application. | Questionable reliability due to wind and ice effects. | No safety problems. | May have detrimental effects if it becomes dispersed. | Very low (power required during application only). | Not feasible in locations with frequent traffic; could be used to allow early navigation season startup. |
| 1.7 - Floats and Pontoons | Very effective in limiting ice growth. | Low to Medium cost. | Prefabricated off-site; towed to site. | None for this application but submersible pontoons common, e.g., semi-submersible. | Should be very reliable. | No safety problems. | No negative environmental effects. | Very low (power required to raise and lower pontoon). | Universal application but may need auxiliary boom or flow developer to minimize ice build-up in front of dock. |
| 2 - ICE BREAKING | | | | | | | | | |
| 2.1 - Conventional Icebreaker | Effective in weakening ice but not in controlling its growth; accelerates ice buildup. | Very high. | Conventional construction. | Universal precedence. | Very reliable. | No safety problems. | Possible oil spills; otherwise, compatible. | Very high; depends on design but in range of 15 - 20 MW for tug in Arctic ports. | Universal application; creates more ice but aids vessel in docking. |

Table 7.1
General Evaluation of
Ice Control Techniques - 3

| | Evaluation Consideration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Effectiveness | Capital Cost | Construction | Precedence | Reliability | Safety | Environmental Effects | Operational Power Requirement | Application to Study Ports/Harbours |
| 2.2 - ACIB/Ship Combination | Effective in breaking uniform ice; ice control similar to that of conventional icebreaker; not proven in rough ice. | High to very high. | May be some construction problems; existing units constructed in Canada. | Tests on Great Lakes; Churchill, Manitoba; and in Alaskan Beaufort Sea. | Some problems with test vehicles; reliability in rough ice doubtful due to skirt vulnerability. | No safety problems. | Comparable with conventional icebreaker. | High to very high. | Not proven in harbours with rough track from repeated passages; needs further R&D. |
| 2.3 - Archimedean Screw Tractor (AST) | Not effective alone as ice control tool; primarily a work vehicle. | Very dependent on ice thickness to be broken; medium to high cost for Arctic. | No apparent construction problems; prototype constructed in Japan. | Prototype tests conducted in Thunder Bay March 1982; similar unit tested in USSR. | Not proven but probably quite reliable. | No safety problems. | Similar to conventional icebreaker. | Depends on use but probably medium requirement. | Needs modifications to be effective as ice control tool. |
| 2.4 - Self-Propelled Mechanical Ice Cutter (MIC) | Effective in tests in uniform ice. | High. | Should not be construction problems. | Tests on lake in northern USA and rivers in USSR. | Not proven; depends largely on blade durability. | No safety problems. | Similar to conventional icebreaker. | High. | Universal application in uniform ice; not proven in rough ice; may be limited in number of passes it can make in one area; needs further R&D. |
| 2.5 - Explosives | Effective in breaking ice jams. | Low cost; depends on frequency of use. | No construction involved. | Traditionally used to break ice jams. | Depends on method of deployment. | Could be dangerous. | Possible detrimental effect on marine life. | Very low. | May be appropriate for any port/harbour with careful design and implementation. |
| 2.6 - Thermal Ice Cutting | Limited effectiveness. | Depends on degree of R&D; probably low cost. | Can be constructed off-site. | Limited tests in USA. | Not very reliable. | Possible operator safety problems. | No negative effect. | Depends on penetration and travel rates; probably low to medium. | Not appropriate on large scale. |
| 2.7 - High-Pressure Water Jets | Limited effectiveness. | Depends on degree of R&D; probably low cost. | Can be constructed off-site. | Limited laboratory tests in Canada and USA; some tests in SLSA locks. | Not very reliable. | Should be safe. | No negative effect. | Depends on penetration and travel rates; probably medium requirement. | Not appropriate on large scale. |

Table 7.1
General Evaluation of
Ice Control Techniques - 4

| | Evaluation Consideration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Effectiveness | Capital Cost | Construction | Precedence | Reliability | Safety | Environmental Effects | Operational Power Requirement | Application to Study Ports/Harbours |
| 2.8 - Lasers | Limited effectiveness. | Low. | Constructed off-site; assembly on site. | Limited laboratory tests. | Not proven; device itself probably very reliable. | No safety problems. | No negative effect. | Depends on penetration and travel rates; medium requirement. | Not appropriate on large scale; not proven. |
| 2.9 -Chemicals | Limited effectiveness. | Low. | Constructed off-site; assembly on site. | Limited laboratory and field tests. | Not proven; although probably reliable since no moving parts; operation at very low temperatures may by a problem. | Possible safety problems depending on chemical. | Possible adverse environmental effects depending on chemical. | Depends on penetration and travel rates; low to medium. | Not appropriate on large scale. |
| 3 - ICE REMOVAL AND DISPOSAL | | | | | | | | | |
| 3.1 - Towing and Pushing | Not known but could be limited. | Medium to high depending on complexity of installation and support vehicle. | Prefabrication off-site; assembly on site. | No precedence. | Questionable. | No safety problems. | Similar to ice-breaker. | Depends on vehicle; high to very high. | Not feasible with present state-of-the-art. |
| 3.2 - Conveyors and Slurry Pipelines | Very likely limited effectiveness. | Medium to high cost; requires substantial R&D. | Prefabrication off-site; assembly on site. | No precedence for slurrying of ice. | Not very reliable; prone to freeze-up and breakdown. | No safety problems. | May affect microclimate if vast amounts of ice are formed. | Depends on rate and travel distance; medium requirement. | Not feasible with present state-of-the-art. |
| 3.3 - Removal by Lifting | Very likely limited effectiveness. | Medium to high; depends on work vehicle. | Constructed and assembled off-site. | Precedence with back hoes and cranes. | Depends on work vehicle; fairly reliable. | No safety problems. | May affect microclimate if vast amounts of ice are removed and disposed of if one area. | Depends on removal rate; low requirement. | Not feasible on large scale for year-round operation. |

Table 7.1
General Evaluation of
Ice Control Techniques - 5

| | Evaluation Consideration | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Effectiveness | Capital Cost | Construction | Precedence | Reliability | Safety | Environmental Effects | Operational Power Requirement | Application to Study Ports/Harbours |
| 4 - ICE DIVERSION | | | | | | | | | |
| 4.1 - Booms | Effective in areas of moving ice and in minimizing ice buildup in front of dock during vessel departure; would have to be used in conjunction with other techniques. | Low. | Prefabricated off-site; assembled on site. | Several applications in rivers. | Very reliable. | No safety problems. | No negative effects. | No energy requirement. | Might have possibilities in Churchill Harbour and in other harbours if it could accommodate vessel passage. |
| 4.2 - Structures | Effective in river ports or those exposed to moving ice; probably used with other techniques. | Low to medium. | Constructed on-site or off-site and towed to site. | Installations in St. Lawrence River near Quebec City and in McKinley Bay. | Very reliable. | No safety problems. | No negative effects. | No energy requirement. | Would be needed in harbours exposed to prevailing winds; McKinley Bay and in river ports, e.g., St. Lawrence ports, Churchill and possibly Sachs Harbour. |
| 4.3 - Flow Developers | Effective in moving loose ice away from dock and in preventing ice broken by departing ship from entering dock area. | Low. | Little construction involved; off-the-shelf for propeller units. | Installations in Baltic ports and, Great Lakes and St. Lawrence Seaway Authority locks; not tested for use as barrier to ice movement behind vessel. | Reliable; standard components. | No safety problems. | No negative effects. | Very low. | Effective during freeze-up and breakup; not tested for use as barrier to ice movement behind vessel. |

NOTE:

| Operational Power Requirement Rating (MW) | |
|---|---|
| <0.1 | very low |
| 0.1 - 1 | low |
| 1 - 7 | medium |
| 7 - 15 | high |
| >15 | very high |

| Cost Rating (Capital Costs) ($million) | |
|---|---|
| <1 | very low |
| 1 - 5 | low |
| 5 - 10 | medium |
| 10 - 50 | high |
| >50 | very high |

well enclosed, relatively small harbour, no artificial enclosure will be necessary; however, this is unlikely, and in all probability, a curtain or similar barrier would be required to contain the warm water that is discharged into the control area.

A variation on the thermal discharge design that would permit effective heat transfer to be achieved without a curtain barrier is the use of vertical diffusers in close proximity to the undersurface of the ice sheet (see Figure 3-1). Such a system would, however, require a flotation arrangement to allow it to be raised and lowered to accommodate vessel traffic, and its feasibility could be eventually decided by the frequency of ship arrivals. No precedence exists for such a system, although considerable experience exists with flotation and submersible devices for other applications, and it should be relatively straightforward to design an appropriate system based on such experience. The overall reliability might be somewhat less than the more conventional concept since a larger number of working components will have to be incorporated in the design. Operating costs should be less however, for the case of providing heat solely for ice control since better heat transfer will be effected, thereby reducing fuel consumption.

As noted previously, very little information is available on actual installations of diffuser systems to control ice growth. Some experiments have been conducted and applications to Soviet ship repair docks have been given brief mention in the literature (Parfenov, et al, 1973). The most recent and applicable case for arctic considerations is the preliminary design of the ice management system for Bridport Inlet. Standard equipment and fittings have been proposed for that design, and the system is expected to perform with high reliability. Preliminary costs for the piping system for that location are in the order of $1.5 million. The cost will, of course, depend on the size of the ice control area, which for Bridport Inlet, is quite large because of the vessel and dock size.

The ice management system in Bridport Inlet has been designed to allow the ice to be controlled by having it pushed underneath the dock by the vessel while berthing. Greater control of the thermal discharge is then possible without having to provide curtains or other barriers outside the dock, and thereby eliminating any possibility of interference with the vessel.

Thermal discharge systems are basically simple with pumps being the only active equipment that could go out of service. With the proven reliability of pumps, particularly if standby units are provided, a thermal discharge system can be considered to be as reliable as the plant providing the source heat. Clearly, due consideration will have to be given to heat loss from the piping system, and any pipes and pumps above the water surface will have to be suitably insulated. Where possible, system components should be fabricated and assembled in a temperate climate before transportation to the arctic.

Some environmental effects will occur due to entrainment of organisms at the system intake with their subsequent exposure to heat and pumping turbulence and discharge of heat to the ice control zone which may change the thermal and flow regimes of the harbour. Careful design of the system should minimize these effects however.

### 7.1.2 Bubblers

If bubblers are used solely for the purpose of moving bottom water to the ice surface to effect a heat transfer, their effectiveness will be determined by the temperature structure of the water column. If a temperature differential does not exist from top to bottom, the bubbler will be ineffective since only cold water will be brought into contact with the ice sheet. Bubblers are, therefore, not generally applicable to arctic harbours since the water column tends to be isothermal. In a few locations, where the harbour is situated near the outflow of rivers, temperature differences have been observed, and in some cases, bubblers have been effective. Tuktoyaktuk, on the MacKenzie River delta, is probably the best example of such a location. Thus, before the technical feasibility of a bubbler in a particular harbour is ruled out, temperature and salinity measurements of the water column should be made during winter.

On the other hand, bubblers are a particularly suitable technique for use in Great Lakes harbours since the required temperature difference usually exists in freshwater bodies. Numerous bubbler systems have been installed in various parts of the Great Lakes, and some of these have been referred to previously. The use of bubblers has undergone fairly extensive study as part of the Great Lakes Winter Navigation Extension Program carried out by the US Corps of Engineers.

Out of the main advantages of bubbler systems is that they are relatively inexpensive. The system consists basically of air compressors and pipes which are standard "off-the-shelf" items and require only a minimum of adaptation. Manpower requirements would be minimal and could be easily handled by regular harbour personnel.

Components of the system could be manufactured off the site. Assembly and installation at site would be relatively simple and easily accomplished during summer open water conditions. Installation through an ice cover during winter would be more difficult and costly.

Bubbler systems are operational under all temperature, ice and visibility conditions. The main components of the system can be sheltered from atmospheric conditions--the compressors in heated shelters and the piping system in the relatively warm water. Careful installation of the piping system would avoid leaks and subsequent maintenance problems. Anchorage of the pipes may be necessary to prevent damage by currents from the propeller wash created during berthing manoeuvers of vessels and, in some cases, dredging may be required. Possible damage due to anchors would also have to be considered. Plugging of the orifices during inactive periods by organic material or sediment can be avoided by periodic pressurization of the pipes.

Operation of an air bubbler system would possibly have to be interrupted periodically if the danger of producing a large open water area appeared imminent. While this is unlikely, such large areas could result in ice fog at low temperatures which would interfere with vessel docking operations. Intermittent operation would therefore control the ice thickness within acceptable limits without actually producing open water.

It is not expected that significant adverse environmental effects will result from the operation of a bubbler system.

### 7.1.3 Wave-Making Devices

The basic operation of a wave-making device dictates that a free boundary be available at the far end of the ice control zone to accommodate the large quantities of frazil ice produced as a result of the wave action. Theoretical calculations and model studies indicate that this ice could be transported over distances of 10 - 12 km for waves 1-m high, and based on this transport capability, the proponents of the system suggest that it would be effective in locations where fast ice as well as open pack ice and open water exist outside the harbour. The wave-train would maintain an open channel through fast ice and would dispose the frazil ice among the ice floes in a moving pack. However, in the case of a closed pack at the harbour entrance, the system would probably not be effective and icebreaker support might be required. Because of the suggested capability of the system, details from full-scale installations are needed before a definite assessment of its technical feasibility can be made.

The system should have negligible environmental effects.

Effects on harbour operations should be considered in light of the possibility of producing ice fog from the open water. This would be of particular concern during vessel arrival. Shutting the system down a few hours before arrival would allow a thin ice cover to form which would prevent fog formation during this time, but consideration would have to be given to the possibility of otherwise continuous ice fog in the harbour hampering general operations.

### 7.1.4 Ice Dusting

The effectiveness of ice dusting is very sensitive to overall climatic characteristics of the location and weather conditions during the time of application of the dust. Reports on the use of dust indicate varying degrees of success because of this sensitivity. Dusting is not effective as an ice control technique but may assist in melting of the ice during the breakup period. Different types of dust have been used, although coal has been most common because of its high energy absorption characteristics. Indications are, however, that other materials such as sand or grain may be as effective. The advantage of the latter materials, unlike coal, is their environmental compatability. As the tests at Thunder Bay in March 1982 show, however, the performance of such materials is still very much dependent on weather conditions.

### 7.1.5 Insulation

The effectiveness of an insulating cover on a water body in reducing ice growth can be immediately seen from simple heat loss calculations. For example, 15 cm of rigid insulation placed on the water surface would maintain the ice thickness to well under 30 cm even if the temperature remained at -30°C for a 5-mo period. If used in conjunction with some form of thermal discharge, the ice thickness could be maintained at even lower values. Thus, from effectiveness considerations, insulation rates highly.

The feasibility of insulation could be reduced significantly however, depending on vessel traffic. Insulation may be attractive if the objective were to allow for an early start-up to the navigation season; however, for year-round use of a harbour, the insulating cover would probably require replacement often enough to render it unfeasible unless the system design allowed for fast application and retrieval with a reusable material.

From an environmental point of view, rigid insulation such as polystyrene or sulphur foams may contravene the environmental regulations particularly if it becomes broken and scattered by either moving ice, vessel or wind. The use of aqueous foams would surmount any environmental difficulties but could become expensive if it has to be replenished several times during the winter. Costs in the order of $100,000 per application could be expected. The method of application of such foams would require improvement to provide efficient deployment over large areas.

### 7.1.6 Floats and Pontoons

A submersible pontoon should be very effective in maintaining very light ice conditions in the berthing area. It may, however, require support from other systems to do this unless the departing vessel can be stopped off the dock while the pontoon is raised in order to minimize the amount of ice flowing back into the berthing area. The pontoon would be constructed in the south and be towed to the site; on-site assembly should be straightforward but the degree of difficulty will ultimately depend on the arrangement used to guide the pontoon while it is raised and lowered. While there is no precedence for such an application in ice control, submersible pontoons are common and are a basic design feature of semisubmersible offshore petroleum exploration and production platforms.

The technique should be highly reliable and present no safety or environmental problems. The potential problem with ice fog can be avoided by submerging the pontoon before vessel arrival to allow a thin film of ice to form in the berthing area. The cost of such a pontoon, which has an area of about 1,500 $m^2$, would be in the order of $8 million. Operational costs would be minimal.

While this concept appears to have universal application in ice control, further investigation is required to establish its overall feasibility.

### 7.1.7 Enclosures

While enclosures appear attractive because they could provide a favourable working environment while maintaining open water in the berthing area, they have a number of technical problems in addition to their very high capital cost, which would have to be overcome. These refer to possible foundation and anchoring problems, and the difficulty of providing a good seal, yet allowing for entry and exit of vessels. Unless waste heat is available to pump into the enclosure or the enclosure is well insulated, the operational power costs would be prohibitive since high heat loss would be experienced through the covering. In some harbour operations as well, safety considerations would be a major concern.

## 7.2 Ice Breaking

### 7.2.1 Conventional Icebreakers

From an effectiveness point of view, the argument for the use of ice-breaking tugs can be supported on the basis of their universal use as support vessels in harbours. This effectiveness is reduced, however, by the considerable quantities of ice generated by the icebreaker in its movements in the harbour, and strictly speaking, they do not control the ice as such but rather facilitate docking of vessels by keeping the ice in a weakened condition. In an arctic operation, the amount of ice generated over the winter through such means could inhibit docking, and other measures of control could be more effective.

Icebreakers clearly have a very high degree of reliability and probably produce negligible effects on the biological environment. Their most obvious disadvantage for harbour use is their capital and operating cost which is far greater than that of other control techniques. The capital cost of an ice-breaking tug for arctic operation will be in the order of $50 million, while yearly operating costs could be in the order of several million dollars.

Perhaps the overriding argument for ice-breaking tugs in arctic harbours is the psychological effect their presence would have on those involved in winter operations, knowing that a support vessel is available to aid, if necessary, in the operation.

### 7.2.2 Air Cushion Ice-Breaking Bow (ACIB)

The ACIB, in combination with a conventional ice-breaking tug, is a very effective tool for breaking ice and has shown a dramatic improvement in ice-breaking capability over the icebreaker operating alone. To date, testing has been carried out in relatively uniform ice; the system has not been proven in rough ice such as a highly deformed refrozen track, ridged ice or pack ice where floe thickness can vary considerably over short distances. Tests also indicate that the track from this combination is clearer than that from an icebreaker alone. While this is particularly advantageous in a berthing area, it is unlikely that after multiple passages through an area that the track would be very different than that from a conventional icebreaker. The effectiveness of the ACIB combination may then be reduced significantly. The performance of the ACIB has also not been demonstrated in working in ice adjacent to a dock where the ice control problems are most pronounced.

Because the ACIB has a greater ice-breaking capability than an icebreaker alone, power requirements and associated capital and operating costs are reduced. However, eventual costs for an arctic application are difficult to estimate because the system is still going through development changes, and indeed studies are being undertaken to further advance a theoretical understanding of the ice-breaking mechanism. The ideal vessel would probably be a conventional hull form with an integrated air cushion bow. Again, this concept is being pursued in ongoing programs. Whether such a concept or indeed any other air cushion platform will have application in the ice conditions to be experienced in harbours remains to be seen however.

### 7.2.3 Archimedean Screw Tractor (AST)

The AST presently exists in prototype form. It is primarily effective as a work or support vehicle, and is particularly suited to moving in loose and rough ice conditions. While it can be used to break ice, it leaves large slabs in its track which would require moving to facilitate ice control in a harbour. Thus, with the present hull design, it has limited use as an ice control device.

As an icebreaker, its energy requirements are less than those of a conventional ice-breaking ship because it can apply essentially 100 percent of its total weight to the ice sheet to break it. Thus, for equal ice-breaking capability in terms of ice thickness, the capital cost of an AST would be considerably less than a conventional icebreaker. Operational costs would also be less due to smaller crew and fuel requirements.

No costs are available for a unit that would be capable of breaking arctic ice; however, the AST-300, which would be capable of breaking ice 0.5 - 0.6 m thick, would have a capital cost of $750,000. An arctic class unit would presumably cost several million dollars.

While only a prototype presently exists, the AST should have a high degree of reliability since its components are largely standard items and it is powered by a conventional power plant. It has not to date been tested extensively under arctic conditions; however, its performance under such conditions should not be impaired if it is designed properly.

### 7.2.4 Mechanical Ice Cutter (MIC)

The MIC, as currently designed, has been planned for use in relatively uniform ice conditions; as such, the ice cutter has a limited ability with regard to ice type and thickness. It will be most successful in level ice of less than the maximum design thickness; its capabilities in a refrozen track or consolidated pack ice of appreciable thickness will be severely limited. It is claimed that the MIC leaves an ice free track so that it would always be required to operate in uniform ice. However, the ability to leave a clear track will be impaired as the number of passages increases due to the increased buildup of ice to the sides of the track. Therefore, it would probably be necessary to remove the ice at the same time that it is being cut to avoid large thicknesses which the cutter could not handle. Current MIC design does not provide for ice removal, although it might be possible to combine the MIC and conveyor bucket arrangement presented in a previous section of this report.

While mechanical removal is approximately 10 times as energy efficient as melting, it does entail considerable logistic difficulties and, on a large scale, is probably impractical.

The reliability of a MIC would be directly related to the quality of research, development, prototype construction and testing for the specific application. Due to the fact that the cutting blades are exposed and subject to damage, the ice cutter's reliability may be limited.

If a MIC is selected as an integral part of an ice management program in an isolated northern port, a backup cutter will be required if there is any maintenance or repair work which cannot be carried out on location during the winter within a reasonable period of time. The summer season will provide ample opportunity for the annual refit work to be done. It appears likely that this work would have to be done on location and appropriate facilities would be required.

Viability of the MIC will not only be dependent on effectiveness and reliability but also capital costs, and operating and maintenance costs. Neglecting the costs of research and development work, capital costs of a MIC will, most obviously, be related to size. While optimum size can only be determined through detailed research work, a MIC with a 20-m beam would seem to be appropriate for work around dock facilities.

With regard to operating costs, the model tests reported previously indicate that a MIC would require only 70 percent of the fuel requirements of a conventional icebreaker of the same beam. Maintenance costs would probably be similar. It is not possible to be specific on manpower requirements; however, it is to be expected that a MIC will require a full-time operating and maintenance crew. For a 20-m cutter, perhaps 3 or 4 men would be required throughout the winter season.

The use of a MIC would provide no more disruption to the local environment than would a similar sized icebreaker; noise exhaust gases and waste heat would be very similar, and MIC operations should not hinder any plant or harbour operations.

### 7.2.5 Miscellaneous Ice-Breaking Techniques

#### 7.2.5.1 Explosives

While explosives have proved useful in countless cases to remove jams on rivers and in pack ice, their use in harbours, particularly in close proximity to the dock, would have to be carefully controlled. With proper selection of charge weight and spacing, and with due regard to structural and human safety, explosives could have some application to ice control in harbours. They would be more suitable for use in thin ice since the charge weight could be maintained at a low level.

### 7.2.5.2 Thermal Ice Cutting

Thermal ice cutting as an ice control technique has undergone some research, but very little full-scale testing has taken place. Power requirements are high for realistic cutting rates, and removal and disposal of ice is still required once the ice has been cut. It is possible that thermal cutting in a local area could be used near a dock in conjunction with other means such as a flow developer to move the cut ice away from the dock; however, further testing under low air temperatures is necessary to determine the overall feasibility of the technique.

### 7.2.5.3 High-Pressure Water Jets

High-pressure water jet cutting, like thermal cutting, has very high power requirements for realistic cutting rates. The cutting rate and associated power is also sensitive to the air temperature with a considerable reduction in penetration rate at very low temperatures. For ice control in harbours, the technique would therefore have very limited use, particularly in the arctic. Cuts made in the ice would tend to refreeze quickly, and other parallel methods would have to be employed to move the ice away from the control area. Like thermal cutting, high-pressure water cutting could have application as an ice-weakening agent attached to the bow of an ice-breaking vessel; however, the power requirements would again be extremely high. Calculations by Mellor (1974) indicate that, for a vessel travelling at 1.5 m/s through ice 1.8 m thick with a 3-jet system attached to the bow, the power required for cutting would be over 9 MW. For a speed of advance of 2.5 m/s, the power requirement would be 14.5 MW, which is a prohibitive amount of power to be used for an auxiliary device when one considers that Canada's largest icebreaker, *CCGS Louis S. St. Laurent*, has a propulsive power rating of 17.9 MW.

### 7.2.5.4 Cutting with Lasers

From the limited test data available on the use of lasers for cutting ice, it is clear that high powers are required. The efficiency appears to be less than that of thermal cutting (which in turn, is much lower than mechanical cutting). While further test data would be welcome to better assess laser cutting, at this time the method does not appear to be practical.

### 7.2.5.5 Cutting with Chemicals

The technique of cutting with chemicals is still in the development phase. Small-scale tests indicate that cutting rates comparable to mechanical cutting could be achieved. To date, tests have been conducted with ammonia which was available in standard industrial cannisters. To maintain vapour pressure in the system under low temperatures, a heating jacket rated at 3 kW was used; it is envisaged that a portable catalytic propane heating jacket would be used in the final prototype. Considerations are also being given to using ammonium chloride salt which is transportable in bulk form. This salt would have to be heated to its dissociation temperature of 340°C and the resulting products would then react with the ice. One advantage of this technique over thermal or high-pressure water jet cutting is that any residual liquid left in the slot cut in the ice will not freeze because of the freezing point depression. Because the technique is still in the development phase, it is not possible to predict the overall feasibility of the technique. It would appear, however, that some concerns might arise with regard to environmental effects and operator safety.

## 7.3 Removal and Disposal

### 7.3.1 Removal by Lifting

While the physical removal of ice is attractive from a consideration of energy requirements, one must realize that the value calculated previously for minimum specific energy could be increased several times by inefficiencies in the total system. In most cases, the required mechanical energy will be generated by the combustion of a fossil fuel probably in an internal combustion engine whose overall efficiency is probably less than 30 percent. Further inefficiencies, although less, will be incurred in mechanical, electrical or hydraulic transmission systems. Despite these inefficiencies, however, the total energy requirement is still considerably less than that associated with most of the other ice control techniques and the feasibility of ice removal will be determined by other, practical factors. These relate to the volume of ice that would require removal and disposal over an operating season (depending on the vessel traffic these volumes may create insurmountable disposal problems), and the type of vehicle needed to actually remove the ice and work in varying ice conditions. This would require substantial research and development. One might envisage, for example, an amphibious vehicle like the AST with the required hull form or attachments to remove ice and transport it to a disposal site.

### 7.3.2 Towing and Pushing

The analysis presented previously for pushing ice slabs pertains, strictly speaking, to the movement of slabs through open water. While the energy calculations are of some use, particularly for comparative purposes, the application to pushing broken or brash ice out of a clogged channel may be somewhat tenuous. The limitations on such a technique arise however from practical and operational considerations rather than energy considerations. Over a winter, the volume of ice to be moved would be very large if the frequency of vessel traffic is high because the removal of ice from the ice control zone repeatedly exposes the water surface to the atmosphere and consequently accelerates the total ice growth over the season. No device or system presently exists for disposing of ice in this manner and considerable research and development would be required to develop such a system.

The method of submerging ice pieces, while requiring comparatively low energy levels, would be of limited use since the disposal area under the undisturbed ice sheet to the side of the control zone would eventually become "choked" due to the increased accumulation of ice below the sheet.

### 7.3.3 Conveyors and Slurry Pipelines

Conveyors have been used extensively for the movement of materials, especially in the mining of coal or ore. The problems of operation and maintenance in the arctic environment, especially when the conveyors can ice-up very quickly, are considered too severe for practical adaptation. It is very likely that the slurry pumping of ice is technically possible; however, the information necessary to undertake such a design is not presently available and could only be obtained through experimentation and pilot projects similar to those undertaken in the slurrying of coarse coal. Such experimentation would also be necessary to assess the impact of dumping an ice slurry under an ice sheet.

Due to the experimental and developmental nature of the design required, any estimate of cost would be very difficult to obtain.

No precedents have been established in the slurrying of ice in any environment; therefore, no realistic assessment of reliability can be made. However, ice should be easier to transport than soils, rocks or minerals since it is almost neutrally buoyant in water.

The system must, in the main, be constructed on site. Installation of an underwater pipeline (for submerged slurrying) would probably extend over two seasons at least, depending on the distance to the dumping location chosen. Pumps of the capacity indicated would produce a high demand for electrical power while operational.

The reliability of such a disposal scheme is very questionable, since it has been shown that the pipe can freeze up quickly, and for a submerged pipeline, the ice can pile up below the natural ice sheet to such a depth that the flow will eventually be blocked.

Due to the problems of transport and disposal of the ice, it is considered that this method of ice removal is not technically feasible. Mechanical failure, the problems of operations and maintenance, and the high costs of the necessary marine support will also act as major drawbacks for this scheme.

## 7.4 Ice Diversion

### 7.4.1 Booms

As discussed previously, booms have their primary application in river ice and have had little application in harbour areas. Sufficient precedence has been established with the construction, installation and operation of booms to determine an appropriate design for any site at which moving ice could create problems. For the case of frequent deployment and retrieval of a boom as might be considered for the prevention of ice buildup in front of a dock due to displacement by an exiting vessel, special design methods would have to be considered. Since they represent a totally passive technique of ice control, energy costs for operation are probably nonexistent other than as associated with maintenance. The capital costs depend on the length of the boom, the ice forces and the water depth, and would vary with the site. The technique would be completely safe from environmental and human considerations. The boom should be designed so as to have negligible impact on harbour operations.

### 7.4.2 Structures

Structures are an effective, passive means of diverting ice away from a control zone in a moving ice regime. Capital costs would depend on the type and size of structure; operating and maintenance costs would be negligible. It is unlikely that they would have any detrimental effect on the environment and with a proper design, the effect on any harbour operation should be nonexistent. In short, for their limited application, they are an obvious and effective means of ice control.

### 7.4.3 Flow Developers

Flow developers could be effective in moving loose ice away from the dock thereby assisting in berthing and in preventing ice from entering the berthing area when a vessel is leaving the dock. Their capital and operational costs would be very low, and appropriate units, particularly propellers, should be available as off-the-shelf items. They have some precedence in the Baltic and bubbler units have been used in locks on the St. Lawrence Seaway to control ice movement. The reliability of such systems is quite high and no negative safety or environmental effects should result from their use.

# 8. CASE STUDY

## 8.1 Introduction

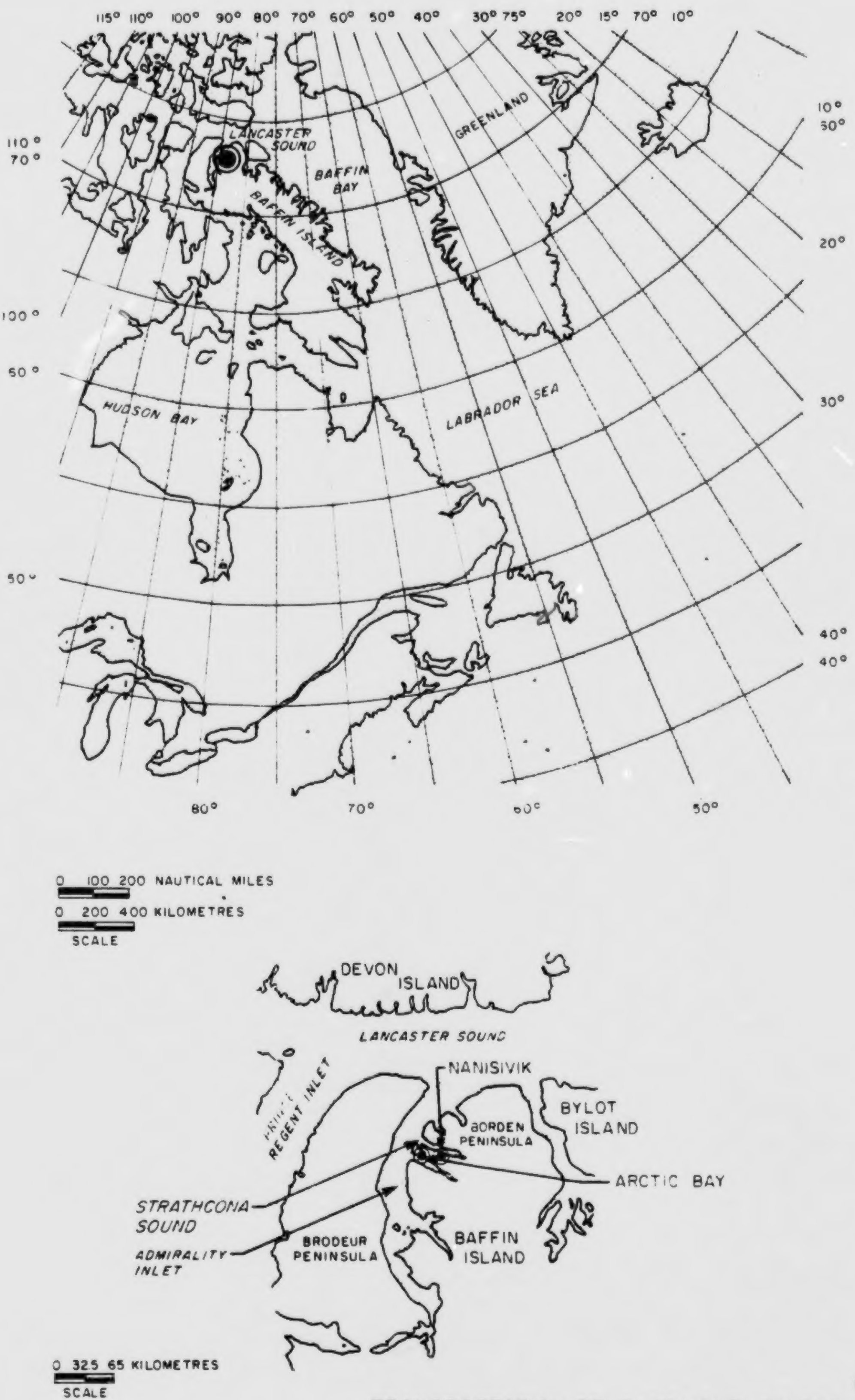
In this section of the report, the ice control problems at the port of Nanisivik, Baffin Island, and possible ice control techniques for this port are considered. A detailed description of the environmental conditions in the harbour is presented and a number of ice control techniques are evaluated. Recommendations for the most appropriate control techniques are then made. This case study illustrates one process that could be followed in the design of an ice control system for ports and harbours.

Nanisivik is located on the south shore of Strathcona Sound, a deep water fjord off Admiralty Inlet on the northern extremity of Baffin Island. Admiralty Inlet leads into Lancaster Sound, the main east-west route through the Canadian high Arctic (Figure 8-1). The port of Nanisivik and the townsite were constructed in the period 1974 to 1978 to support the Nanisivik mines which started production of lead and zinc ore in late 1976. The shipping season, which was a 2-month operation at the start 5 years ago, is now a 5-month operation with the ice-breaking cargo ship M.V. Arctic being used extensively.

## 8.2 Ice Control Problems

To date, no severe ice problems have been experienced at Nanisivik and the M.V. Arctic, which is considered to be an Arctic Class II ice breaking vessel, has managed to extend the original navigation season by 3 months. In 1982, the M.V. Arctic arrived at Nanisivik on June 30 which is the earliest opening date so far. The last shipment out of Nanisivik in 1982 is scheduled for November 24. The opening date for navigation is more dependent on ice conditions in Admiralty Inlet since ice there usually breaks up later than ice in Strathcona Sound. Breakup in the Sound is aided by the inflows from the Strathcona River and Nanisivik Creek in late spring, this water actually flowing around the dock and causing the ice there to deteriorate faster than the rest of the Sound.

However, if cargo ships do negotiate Admiralty Inlet at progressively earlier dates in the future, possibly with the aid of large icebreakers, the most significant ice problem may occur at the dock in Strathcona Sound. This is due to the large buildup of ice at the face of the dock because of tidal effects. This ice reaches its maximum thickness and extent in late winter/early spring and would present a considerable obstacle to docking during that time. (This assumes an extended seasonal operation only; a year-round operation could change this ice regime depending on the frequency of vessel traffic.)


115° 110° 100° 90° 80° 70° 60° 50° 40° 30° 75° 20° 15° 70° 10°
110° 70°
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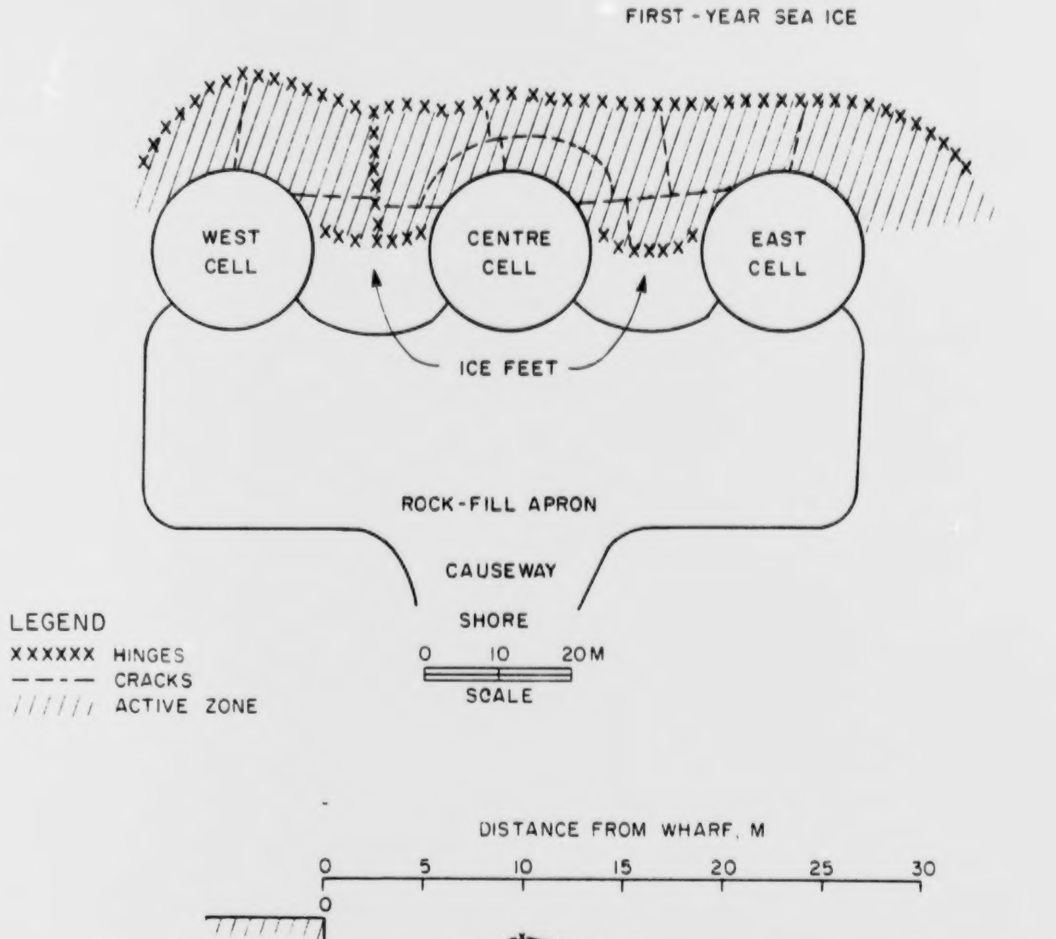
LANCASTER SOUND
BAFFIN BAY
BAFFIN ISLAND
GREENLAND
HUDSON BAY
LABRADOR SEA
0 100 200 NAUTICAL MILES
0 200 400 KILOMETRES
SCALE
DEVON ISLAND
LANCASTER SOUND
PRINCE REGENT INLET
NANISIVIK
BORDEN PENINSULA
BYLOT ISLAND
ARCTIC BAY
STRATHCONA SOUND
ADMIRALITY INLET
BRODEUR PENINSULA
BAFFIN ISLAND
0 32.5 65 KILOMETRES
SCALE

FIG. 8-1

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS
LOCATION MAP FOR NANISIVIK

The ice features near the dock at Nanisivik have been described in detail by Frederking (1977, 1980) from on-site observations carried out during the winters of 1975/76 and 1978/79. Figure 8-2 shows the general layout of the Nanisivik dock and the ice features as seen in March 1979. Because of tidal action, a network of hinges and cracks forms to accommodate the differential vertical movement between the ice cover and the wharf. (Frederking defines hinges as features across which relative rotations of several degrees occur, while cracks involve rotations of less than 1 deg.) This area of cracks and hinges, which forms a transition from the fixed ice foot and wharf, and the free-floating ice cover is designated as an active zone, and it appears that this zone forms in the same systematic pattern each winter. In early winter (November), Frederking reports the existence of an ice "bustle" (lateral growth from freezing of a layer of water on the dock cells during falling tide) and an active zone 2 - 2.4 m wide, which was hinged at the junction with the natural ice and moved up and down with the tide, and was occasionally flooded when the edge at the cells was tilted downward (against the bustle) during high tide. By midwinter (February), this flooding occurred during nearly every high tide and new layers of ice were grown not only on the horizontal surface but also at the vertical face of the cells. It was found that the buildup of ice at this face, which averaged about 2 cm per tidal cycle, was very similar to the horizontal movement of the natural ice. Frederking speculates that this movement was due to the thrust developed from the buildup of ice on the vertical face of the active zone. By the end of June, the width of the active zone was over 11 m, the thickness, at 5 m, was about three times that of the natural ice, and the zone had broken into segments which floated freely between the "natural" ice cover and the wharf. It is thus considered that this very thick active zone would present problems for docking vessels early in the season in an extended shipping operation. In a year-round operation, it could combine with ice buildup from repeated passages through the winter to result in a compounded problem, although it is more likely that, in this case, the reduction in ice consolidation due to vessel traffic could lessen the problem due to tidal effects. The major problem would then be that due to accelerated buildup of ice from frequent vessel passages.

In this case study, primary emphasis is placed on a consideration of the problem presented by ice formation due to tidal effects in an extended season operation. This problem may be approached in one of two ways. An ice control technique could be put in place which would operate either throughout the winter to prevent the formation of the so-called active zone, or only prior to startup of the navigation season to remove the ice that has formed in the active zone. In the following paragraphs, a procedure is presented for the consideration and evaluation of ice control techniques for both applications. This procedure, while being applied in this case to Nanisivik, illustrates an approach


FIRST-YEAR SEA ICE
WEST CELL
CENTRE CELL
EAST CELL
ICE FEET
ROCK-FILL APRON
CAUSEWAY
SHORE
LEGEND
XXXXXX HINGES
– – – – CRACKS
////// ACTIVE ZONE
0 10 20M
SCALE
DISTANCE FROM WHARF, M
0 5 10 15 20 25 30
0
5
10
DEPTH, M
WHARF CENTRE CELL
HIGH TIDE
0
5
10
WHARF CENTRE CELL
LOW TIDE

SOURCE FREDERKING, 1980

FIG. 8-2

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

ACRES

ICE FEATURES AT NANISIVIK DOCK, MARCH 1979 that could be applied to the design of ice control techniques for any location. The procedure here is first to establish a list of design parameters which refer to the environment at the site, the dock features (in cases where docks already exist), and characteristics of a typical vessel to be used at the site. Criteria will then be established for the selection of ice control techniques. The preferred procedure, however, would be one in which the selection and design of ice control techniques forms a part of the overall design, particularly the dock design; in the case study, the procedure will be to evaluate a number of ice control techniques that will be compatible with an existing structure.

Once the design parameters for the site and design criteria for ice control techniques have been established, a number of possible control techniques will be considered. Those which are clearly incompatible with the criteria and system parameters will be discarded and the resulting short list of techniques evaluated in some detail to establish the most appropriate solution(s).

## 8.3 Design Considerations

To aid in the evaluation and selection of possible ice control techniques, a number of system parameters should be established. The following listings summarize data on the environment at Nanisivik, the characteristics of the dock structure, a cargo ship operating at the port, and present a number of criteria to be considered when evaluating ice control techniques.

### 8.3.1 Design Parameters

#### Climate

Climate data for Nanisivik have been largely obtained from records for Arctic Bay which is 30 km to the southwest. These records cover the period 1941 to 1970. Some data are available for Nanisivik itself for the past 5 years.

| | |
|---|---|
| Mean annual temperature | -13.7°C |
| Minimum mean daily temperature | -17.2°C |
| Maximum mean daily temperature | -9.5°C |
| Extreme minimum temperature | -53°C |
| Extreme maximum temperature | +22.2°C |

| | |
|---|---|
| Mean freezing degree-days | 5,500°C-d |
| Mean melting degree-days | 370°C-d |

The action of winds is taken into account when considering ice movement and pileup, forces on docking vessels and other structures and systems that may be vulnerable to damage by high winds.

| | |
|---|---|
| Mean wind velocity | 2.2 m/s |
| Extreme wind velocity | 21.1 m/s |

| | |
|---|---|
| Predominant wind direction | NW |
| summer | NW |
| fall | NNW |
| winter | N and S |
| spring | NNW |

Precipitation at Nanisivik is very light with 40 percent of the total annual precipitation falling as rain during the short summer season.

| | |
|---|---|
| Mean annual total precipitation | 12.6 cm |
| Mean annual total snowfall | 71.1 cm |
| Mean total annual snow cover | 35.6 cm |

## Oceanography

Very little information is available on the oceanography of the Nanisivik site and the following are largely approximated from short-term observations. Currents are mainly tidal and are confined to the upper 7 m of the water column. No data are available on the salinity and temperature structure of the water; however, it is quite likely that during winter no stratification exists and the water column is isothermal and isohaline.

| | |
|---|---|
| Mean tide range | 1.5 m |
| Large tide range | 2.5 m |
| Mean surface current | 0.25 m/s |

The wave climate is generally calm due to the protection of hills against winds and short fetches which vary from 5 km from the north to 50 km from the west. The wave height used for the dock design was hindcasted from Arctic Bay wind data.

| | |
|---|---|
| Maximum wave height | 2.4 m |

## Ice

The ice in Strathcona Sound begins to form in early October and remains fast until breakup in late June. The ice responds to the tide which causes a thick zone of ice to be built up at the dock. This zone could be 3 times as thick as the normal ice thickness and extend several metres from the dock.

| | |
|---|---|
| Maximum uniform mean ice thickness<br>(Calculated from mean freezing degree-day record.) | 2.0 m |

## Dock Structure

The dock structure at Nanisivik has the following specifications.

| | |
|---|---|
| Approximate length of dock | 100 m |
| Construction | 3 steel sheet-pile cells 21-m diam spaced at 38-m centres; gravel-filled and connected by causeway to shore |
| Minimum water depth at dock | 12 m |

Vessel Characteristics

The following ship characteristics are those of the icebreaking cargo ship M.V. Arctic which is presently operating to and from Nanisivik from late June to late November. It is quite likely that, if the season opening were moved ahead to earlier in the spring, the M.V. Arctic would not be able to navigate the ice of Admiralty Inlet and Strathcona Sound independently. If and when this happens, it is likely that more powerful ships would berth at the Nanisivik dock.

| | |
|---|---|
| Length, overall | 196.7 m |
| Beam | 22.9 m |
| Draft | 10.9 m |
| Displacement | 38 100 tonnes |
| Power | 11.0 MW |

### 8.3.2 Design Criteria

A number of criteria were established previously for a general evaluation of ice control techniques. These criteria are now used to examine, in some detail, possible solutions to the ice control problems that could be expected at Nanisivik in an extended operation. For the sake of completeness, the various criteria that were used in the previous evaluation and which would be used in designing an ice control system are repeated here.

Effectiveness

The system must first of all be technically effective in that it must show a significant probability of solving, or at least reducing, the ice control problem.

The most effective (but not necessarily most feasible) system is one which deals with problems directly--that is, prevents ice from adhering to the dock in the present case.

Cost

The system life cycle costs, and replacement costs, should be kept to a minimum.

### Precedence

While little precedence exists for most ice control techniques, particularly under arctic conditions, the performance of the system should be predicted with a high level of confidence, either by theory or by extrapolation of similar applications whenever possible.

### Reliability

The system must be operational under all ice and weather conditions. Proper functioning of mechanical equipment and piping must be ensured. Critical functions of the system should have adequate backup or duplication (the system should have automatic control and check procedures, if possible). Replacement parts should be either stored on the site or be capable of quick delivery.

### Safety

The system must not have adverse effects on the safe operation of the harbour facilities. The system must also have acceptable human safety limitations.

### Construction

The system should, if possible, be capable of being manufactured and tested off the site prior to installation. The construction procedure on the site must be examined thoroughly in order to avoid operations which may be normal in temperate climates but not possible or very difficult in an arctic environment.

### Power Requirements

Power requirements for system operation should be kept to a minimum; very large power requirements would render a system unfeasible in remote areas.

### Environmental Effects

The operation of the system must not have adverse effects on the environment in terms of the physical and biological environment (i.e., air quality, water quality, land alteration, noise, marine and terrestrial flora and fauna). The effects of ice fog must be minimized to ensure safe vessel berthing operations.

## 8.4 Preliminary Evaluation of Techniques

A general evaluation of a number of ice control techniques should be first carried out. From this evaluation, a number of possible solutions can then be identified and these would undergo a more rigorous evaluation. By using the general evaluation conducted previously and keeping in mind the particular ice problems at Nanisivik, the following systems can be ruled out as providing a solution to the ice control problems at Nanisivik.

### Bubblers

Although data on the temperature and salinity structure of the water column in Strathcona Sound are not available, in all likelihood, no thermal reserve exists at depth to provide energy that could be transferred to the ice sheet by a bubbler system. Therefore, a bubbler system would not be feasible.

### Wave-Making Devices

The success of a wave-making device depends on the availability of open water or moving ice at some distance from the ice control zone to serve as a disposal area for frazil ice carried along in the waves created by the device. Since the Nanisivik dock is far removed from any such area, the device would not be feasible.

### Enclosures

For the present application, an enclosure would be too expensive and this, together with construction difficulties, lack of precedence, etc, would render it unfeasible.

### Dusting

Dusting is of limited effectiveness and then only during the breakup period. Since the present application entails the control of ice in late winter or spring, the method would not be appropriate.

### Insulation

In the form of rigid sheets or foam, insulation would not be applicable particularly in view of the manner in which the ice growth occurs in the present case, this growth being mainly at the top surface of the ice. Insulation would also be vulnerable to movement and breakup from winds and the rotating ice in the active zone. It may be possible to use insulation in another manner, and this is considered in a later paragraph.

### Conventional Icebreakers

Because of the large ice thicknesses near the dock at Nanisivik at the end of winter, it would be very difficult for an icebreaker to manoeuver close enough to the dock to break this ice. At the present time, the largest icebreaker in the Canadian fleet would probably have to back and ram to move through this ice and this is not desirable near the dock because of possible damage to either the vessel or dock, or both. It is also quite likely the vessel could not transit the fast ice in Admiralty Inlet and Strathcona Sound during late winter or early spring. It is not feasible to engage an icebreaker over the entire winter to keep the ice near the dock broken up because of the large operational costs, and the capital costs of a new ice-breaking tug capable of breaking up the ice in late winter would appear to make the use of icebreakers unfeasible.

### ACIB/Ship Combination

The above comments on conventional icebreakers also apply largely to an ACIB/ship combination. In addition, the present state of development with this technique and the lack of testing in the Arctic make it unfeasible for the present requirement at least for the next few years. Further developments, particularly with the integrated bow cushion, may make it more attractive in the future.

### Conveyors and Slurry Pipelines

These would not be effective in the present application. In addition, costs would be high and substantial power would be required.

### Ice Diversion

All three techniques--booms, structures, flow developers--could have application in a year-round operation, particularly in conjunction with other techniques; however, they are not considered to be applicable to alleviating the problem at Nanisivik which is the prevention or removal of ice to enable an earlier startup to the navigation season. Two of the techniques--booms and flow developers--may have application to the problems created by a moving ship in the berthing area during a year-round operation. Structures may have a marginal use as a containment feature to be used in conjunction with a warm water discharge. Such an application does not appear feasible for limited season operation; moreover, the effect on ship manoeuverability and harbour operations could be detrimental.

## 8.5 Evaluation of Candidate Techniques

The following techniques hold some promise for solving the ice control problem at Nanisivik and these are now discussed in some detail. In evaluating these techniques, the criteria established previously were used in conjunction with a rating system. Each of the criteria was scaled from 1 to 5 with 5 being a high score. Because some criteria are more important than others to the overall feasibility of a technique, the criteria were also weighted on a scale from 1 to 5. These weighting factors are as follows:

- effectiveness (5)
- cost (4)
- precedence (1)
- reliability (4)
- safety (5)
- construction (3)
- power (3)
- environment (3).

The total possible score for any one technique is therefore 140 using this rating system. Naturally, these weighting factors are subjective and could vary with the application and the evaluator's perception of the relative importance of each to the overall feasibility of a concept. The evaluation summary is shown in Table 8.1.

## Thermal Discharge

As described previously, there are two basic operational concepts for a thermal discharge system. The simpliest, but less effective, arrangement is to discharge warm water horizontally through a series of nozzles or diffusers at the dock face. In order for this system to be effective, the warm water must be contained, otherwise, dilution will continually occur with the ambient water and cause severe temperature reductions. This, together with low velocities of the discharge water away from the nozzles, would result in negligible heat transfer to the ice surface.

The other concept is to discharge the warm water vertically from a diffuser arrangement that covers the desired ice control area and is positioned close to the underside of the ice cover by means of flotation devices. While this is physically a more complicated arrangement, it is expected to be very effective in reducing ice thickness.

Since waste heat is not available at Nanisivik, water from the harbour would have to be heated solely for the purpose of ice control. This necessity may make the concept unattractive. Because of the nature of the ice buildup due to tidal action--that is, flooding and growth at the top surface rather than at the bottom surface as occurs with the natural ice cover--it does not appear reasonable to use thermal discharge throughout the winter in an attempt to minimize this ice buildup. Instead, the warm water should be discharged under the ice a sufficient period in advance of the scheduled opening date of the shipping season to result in the desired ice thickness at that time. Because of the large ice thickness, negligible heat loss will occur through the ice sheet to the atmosphere.

If the ice thickness in the active zone is 5 m and the area of the zone is 10 m by 100 m, the minimum power input to reduce this thickness to 2 m over a 15-d period is 0.40 MW assuming 100 percent efficiency. If the water is heated in a conventional boiler with an efficiency of 80 percent and the

TABLE 8.1

CASE STUDY EVALUATION

| Ice Control Technique | Evaluation Criteria: Effectiveness | Rating | Cost | Rating | Precedence | Rating | Reliability | Rating | Safety | Rating | Construction | Rating | Power | Rating | Environment | Rating | Overall Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Thermal Discharge (vertical diffuser) | Depending on system parameters, should be very effective in reducing thick ice cover. | 25 | Low capital costs, medium operating costs. | 16 | Saginaw Bay tests; general thermal discharge from power plants, etc. | 3 | May be some problems maintaining proper orientation. | 16 | No safety problems. | 25 | May be some problems in installation. | 12 | May be higher than other concepts but total energy may be less than with Technique 3. | 6 | May be minor effect. | 12 | 115 |
| 2 Floats and Pontoons | | | | | | | | | | | | | | | | | |
| 2a Alternative 1 (fixed frame & sliding face) | Depends on quality of seal and sliding joint. | 20 | Fairly high capital cost, $2.7 million. | 8 | Sliding fender with teflon surface used in Cook Inlet. | 2 | Possibility of jamming. | 12 | No safety problems. | 25 | Assembly should be done in summer; may be problems with connecting joint. | 9 | No power required unless heating of seal needed. | 12 | Negligible effect. | 15 | 103 |
| 2b Alternative 2 (fixed frame with low friction coating) | Not effective unless heat used; then similar to Technique 3. | 5 | Lower than Technique 2a less than $1 million. | 12 | No precedence. | 1 | No moving parts. | 20 | No safety problems. | 25 | May be problems during assembly. | 12 | Needs heat to be effective. | 9 | Negligible effect. | 15 | 102 |
| 2c Alternative 3 (floating pontoon) | May have to use heat to ensure effectiveness (prevent ice between cells and pontoon). | 20 | Similar to Technique 2a. | 8 | No precedence. | 1 | Should be reliable. | 16 | No safety problems. | 25 | May be problems during assembly. | 12 | May need heat at cell surface, otherwise no power required. | 12 | Negligible effect. | 15 | 109 |
| 2d Alternative 4 (concrete barge) | Similar to Technique 2c; will have to ensure vertical movement only to prevent ice formation. | 20 | High, $6.6 million. | 4 | No precedence for such an application, although, floating docks in Alaska. | 2 | Simple operation; should be reliable. | 16 | No safety problems. | 25 | May be problems during assembly. | 12 | No power required. | 15 | Negligible effect. | 15 | 109 |
| 3 Heating Systems | Most effective method of preventing ice formation due to tides. | 25 | Depends on system but in order of $100,000 to $200,000 capital costs. | 16 | Heating systems used in docks on St. Lawrence and in lock walls. | 5 | Depends on power supply; should be very reliable. | 20 | No safety problems. | 25 | May have to remove concrete deck; still simple construction. | 12 | Lower power than with Technique 1 but energy expended may be higher. | 6 | Negligible effect. | 15 | 124 |

Table 8.1
Case Study Evaluation - 2

| Ice Control Technique | Evaluation Criteria<br>Effectiveness | Rating | Cost | Rating | Precedence | Rating | Reliability | Rating | Safety | Rating | Construction | Rating | Power | Rating | Environment | Rating | Overall Rating |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 Cutting and Removal | Effective in removing ice in berthing area after formation. | 25 | Depends on rental and freight but should be low; costs per year approximately $100,000. | 16 | Lots of precedence in Arctic. | 5 | Depends on machinery used but should be reliable if equipment is well maintained. | 16 | Must consider bearing capacity of ice, although, crane can operate from dock. | 20 | No construction involved. | 15 | Low power requirment, long-term energy less than with Technique 3. | 9 | Negligible effect. | 15 | 121 |
| 5 Explosives | Effective in breaking ice to certain maximum thickness; ice may still need removal which could be difficult. | 15 | Very low cost. | 20 | Little precedence in harbors; general use in river ice jams. | 4 | Generally reliable, although misfirings are common; charges must be watertight. | 12 | Extreme care must be used for both human and structural safety. | 5 | No construction involved; some preparation and drilling through ice. | 15 | No power required. | 15 | Possible effects on marine life. | 12 | 97 |

NOTE: Rating Scheme

Scale: 1 - 5 (5 high)
Weighting: 1 - 5

| | | | |
|---|---|---|---|
| effectiveness | (5) | construction | (3) |
| cost | (4) | power | (3) |
| precedence | (1) | environment | (3) |
| reliability | (4) | safety | (5) |

Rating = scale rating X weight factor (maximum: 140) efficiency of heat transfer to the ice surface were 50 percent, the power requirement would be 1 MW. The required pumping rate of water to achieve the desired heat transfer would be 0.039 $m^3/s$ if the water were to undergo a temperature change of 10°C.

For test purposes, a piping network could be fabricated from plastic pipe with holes drilled in the pipe at an interval determined by the depth of installation. For such an arrangement, consisting of a 2.5-cm pipe every metre over the entire area of 100 m by 10 m, it is estimated that the system costs would be less than $100,000 including costs of pump, heater, flotation chambers and air compressor.

The system would have to be installed during the summer period and sit on the sea bottom until required. It would then be floated to the desired level under the ice cover.

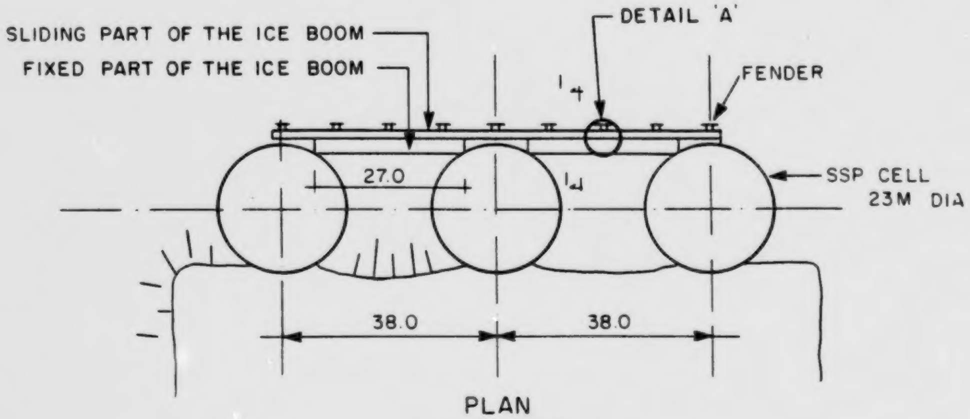
### Floats and Pontoons

A number of new schemes in the form of floats and pontoons at the front of the dock were identified as possible solutions to the ice problem at Nanisivik. Four different arrangements were conceptually designed and these are discussed in the following paragraphs. Each design permits vertical movement with the tide thereby preventing ice formation. They would therefore operate throughout the winter.

#### (a) Alternative 1

This arrangement, which is shown in Figure 8-3, consists of one part fixed to the existing steel sheet-pile (SSP) cells and an outer sliding part to which the fender is attached. Both parts are made from steel and contain insulation to prevent ice buildup between them. The gap between the two parts is also sealed to reduce heat loss and subsequent ice formation. Detail of the sliding joint is also shown in Detail "A"; teflon bearing surfaces would be used to reduce friction between the sliding parts of the pontoon. It is estimated that such a scheme would cost in the order of $2.7 million not including contingencies, engineering and construction management.

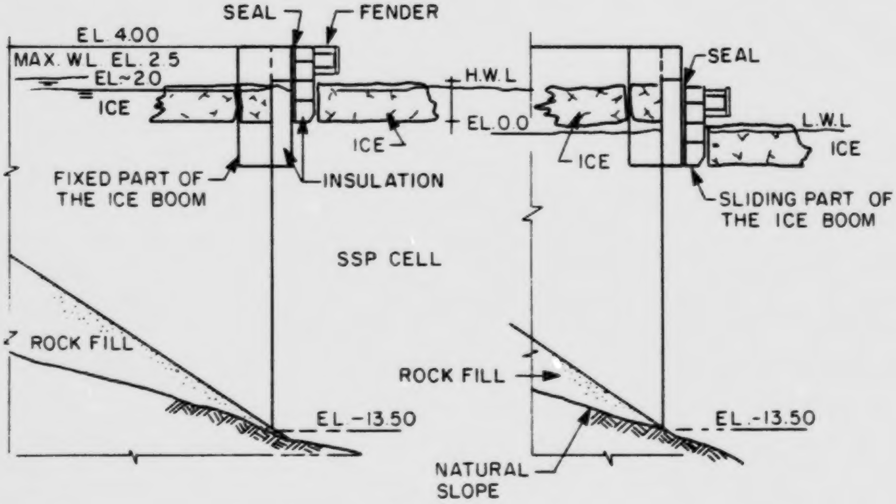
The effectiveness of this arrangement will depend on the ability of the seal to prevent ice formation, thereby allowing the outer floating portion to move up and down freely with the tide. If the sliding movement can be maintained, the arrangement should be very effective. The connection between the two parts is rather complicated and may be a source of problems; the reliability of the arrangement will depend largely on this connection. The only precedent for such an application is in Cook Inlet, Alaska, where teflon sliding joints have been used in the fender system of an oil loading terminal (Gaither and Dalton, 1969). The movement of the fender removes ice that accumulates on the supporting piles.


SLIDING PART OF THE ICE BOOM
FIXED PART OF THE ICE BOOM
DETAIL 'A'
FENDER
1
1
27.0
SSP CELL
23M DIA
38.0
38.0

PLAN

0 10 20

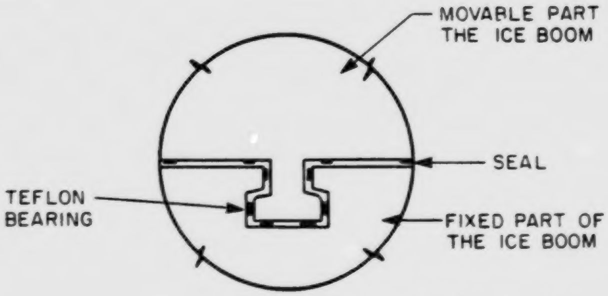
SCALE


SEAL
FENDER
EL 4.00
MAX. WL EL. 2.5
EL~2.0
ICE
H.W.L
EL 0.0
ICE
ICE
SEAL
L.W.L
ICE
FIXED PART OF THE ICE BOOM
INSULATION
SLIDING PART OF THE ICE BOOM
SSP CELL
ROCK FILL
ROCK FILL
EL -13.50
EL.-13.50
NATURAL SLOPE

SECTION 1-1

0 2 4

SCALE


MOVABLE PART OF THE ICE BOOM
SEAL
TEFLON BEARING
FIXED PART OF THE ICE BOOM

DETAIL 'A' (N.T.S.)

(PLAN)

FIG 8-3

TRANSPORTATION DEVELOPMENT CENTRE

ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

AGRES

SLIDING FENDER ARRANGEMENT

Construction of the system would have to be carried out during the summer period; the units would be prefabricated in the south and barged to the site in time for the first open water in the area. The summer period should then be sufficient for assembly and installation.

(b) Alternative 2

This scheme is similar to Alternative 1 except that, instead of having an outer sliding part, the outer surface of the part fixed to the SSP cells would be covered with a low friction coating to inhibit ice buildup. Adfreeze forces would then be reduced to a level which would be insufficient to sustain the weight of any significant amount of ice.

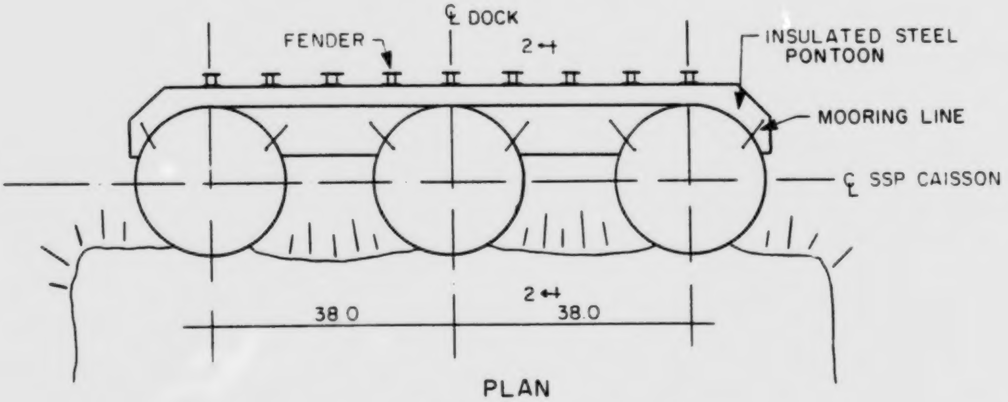
Although this technique could be effective, the information presently available on low friction coatings indicates that the adfreeze strength would still be high enough to support large quantities of ice on the SSP cells. Oksanen (1981) carried out tests on a number of plastics and determined the adfreeze strength as a function of temperature. Extrapolation of the results to an air temperature of -30°C indicates that the strength would be in the order of 0.25 - 0.30 MPa. If a strength of 0.30 MPa is assumed, along with an ice thickness of 2 m, calculations indicate that almost 5 m of ice could be tolerated before the adfreeze bond would be broken. Of course, at Nanisivik, the ice formed on the cells becomes incorporated into the main ice sheet before the ice reaches this extent. It appears, therefore, that coatings with much lower adfreeze strengths are required to effect the desired result. The adfreeze strength could be lowered significantly, however, with interior heating coils and such a heating arrangement is discussed in a later paragraph.

(c) Alternative 3

This arrangement, which is shown in Figure 8-4, consists of a steel pontoon placed between and around the front portion of the SSP cells. The pontoon is insulated to prevent ice formation underneath it. To prevent or weaken any bond between the pontoon and the dock cells due to ice formation, warm air could be pumped into the pontoon to warm up the external walls as shown in the sketch. The cost of the scheme is estimated to be approximately $2.4 million excluding the items mentioned previously. (A variation of this concept for year-round operation has been discussed in Section 3.6.) The unit could be fabricated entirely in the south and be towed to the site for installation during the open water period. Actual installation would consist mainly of mooring the unit to the existing dock structure.

(d) Alternative 4

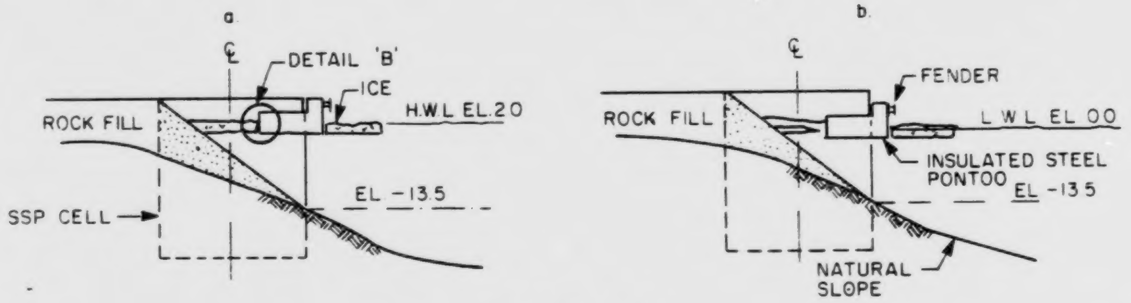
This concept, shown in Figure 8-5, uses a concrete barge fitted with an appropriate fender and installed at the front


℄ DOCK
FENDER
2
INSULATED STEEL PONTOON
MOORING LINE
℄ SSP CAISSON
2
38.0
38.0

PLAN

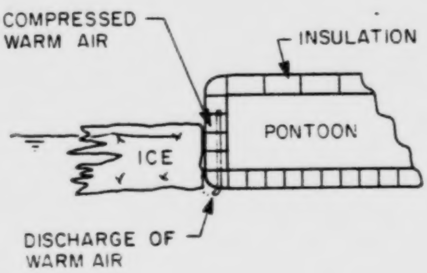
ALTERNATIVE 2

0 10 20 M
SCALE

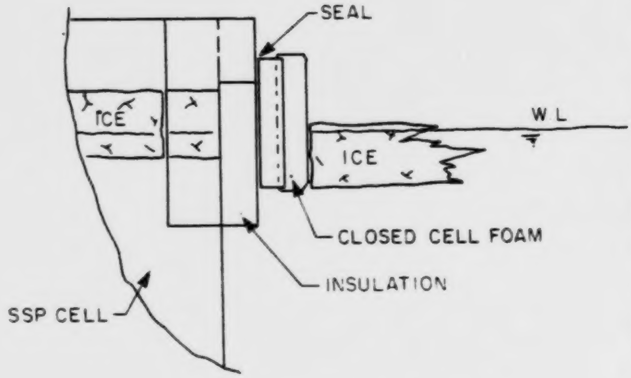

a.
℄
DETAIL 'B'
ICE
H.W.L. EL.20
ROCK FILL
SSP CELL
EL -13.5
b.
℄
FENDER
ROCK FILL
L.W.L. EL. 0.0
INSULATED STEEL PONTOO
EL -13.5
NATURAL SLOPE

SECTION 2-2

0 10 20 M
SCALE


COMPRESSED WARM AIR
INSULATION
PONTOON
ICE
DISCHARGE OF WARM AIR

DETAIL 'B' (N.T.S.)


SEAL
ICE
W.L.
ICE
CLOSED CELL FOAM
INSULATION
SSP CELL

DETAIL 'C' (N.T.S)

FIG. 8-4

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS
FLOATING PONTOON

ACRES

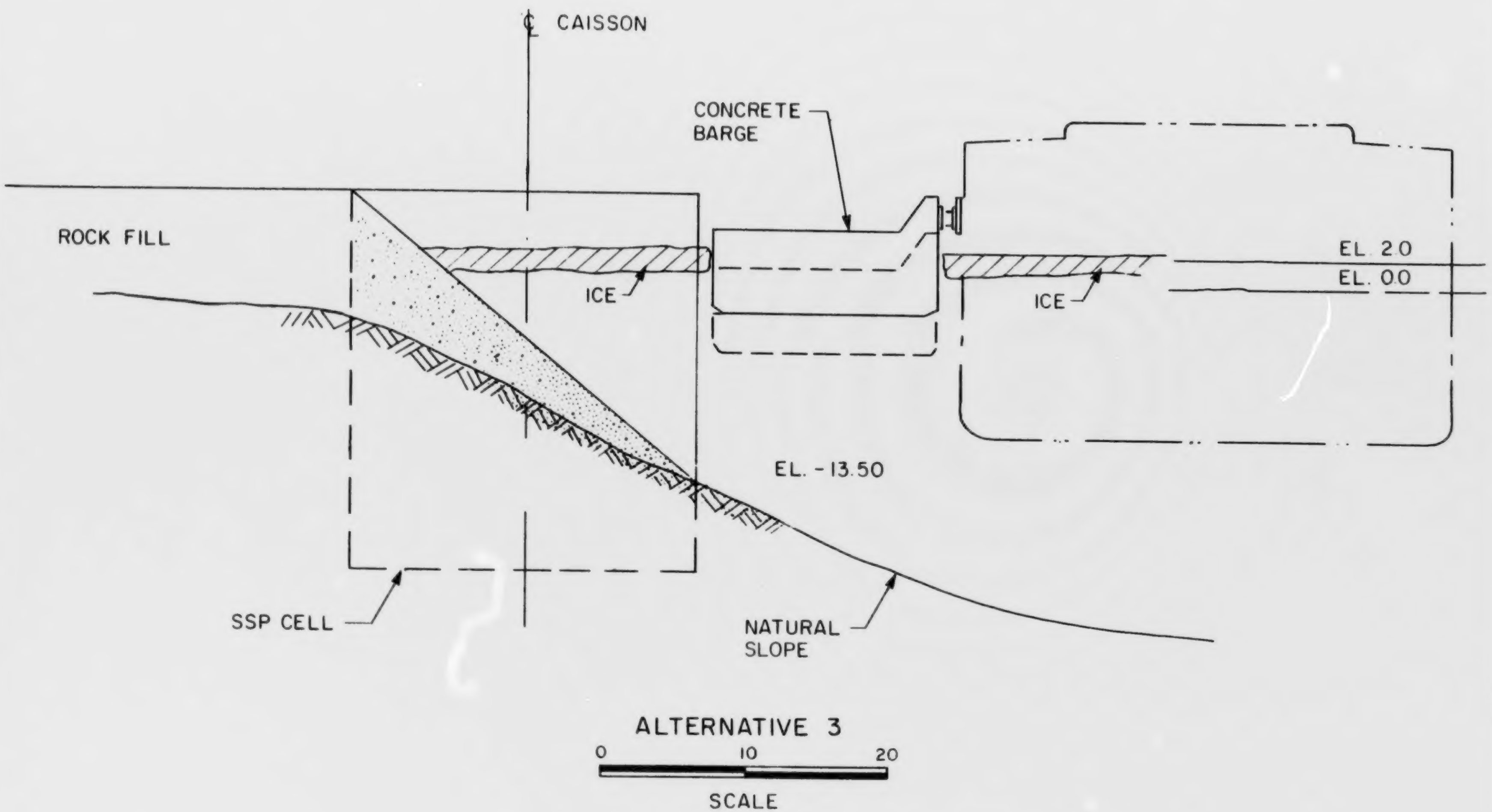

℄ CAISSON
CONCRETE BARGE
ROCK FILL
ICE
ICE
EL. 2.0
EL. 0.0
EL. -13.50
SSP CELL
NATURAL SLOPE
ALTERNATIVE 3
0
10
20
SCALE

FIG 8-5

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS

FLOATING CONCRETE BARGE

ACRES

of the SSP cells. The barge, which is 100 m by 15 m, behaves like a floating dock and shears off any ice built up on the face of the SSP cells as it rises and falls with the tide. The fabrication and towing costs of the barge are estimated to be in the order of $6.6 million not including the previously mentioned items, nor the costs associated with modifications to the loading system to accommodate the effectively greater dock width.

### Heating Systems

By incorporating heating systems into the dock at Nanisivik, it would be possible to prevent the ice buildup on the dock face and the eventual formation of a thick active zone. Two alternatives for heating the cell walls were investigated. In both methods heat is supplied to the inner surface of the cell walls.

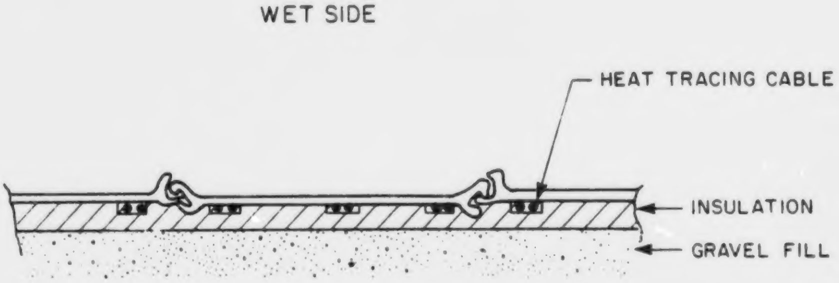
#### (a) Electrical Heat Tracing

In this method, the gravel in each cell would be excavated to the low tide level. Electrical heat tracing wire would be installed up and down each pile, three lenghts to each pile at 15-cm spacing. The cables would be protected by a steel channel strapped to the piles and filled with heat transfer cement. The heat tracing cables would be separated from the gravel fill by a 10-cm thick wall of styrofoam insulation, as shown in Figure 8-6. The individual heat tracing cables can be withdrawn and replaced for maintenance.

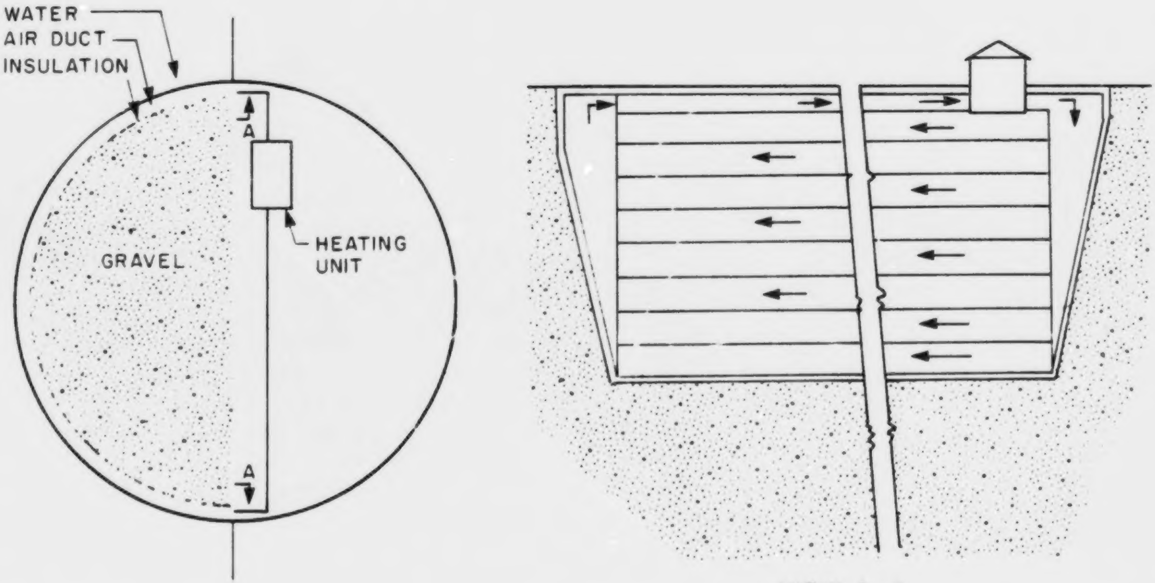
#### (b) Hot Air Heating

In this method of heating the cell walls, the gravel in the cell would be excavated to the low tide level. The cell walls would be sealed water tight. A 15-cm wide air passage would be created on the inside of the cell by installing an inner wall made of a 6-mm thick plate. The inner wall would be tied to the piles by horizontal plates at 30-cm spacing in the vertical direction. Thus, the air space would be divided into horizontal ducts for the passage of air. Vertical plenums would be built at the two ends to distribute air equally into the air passages. The inner wall would be insulated from the gravel by styrofoam. The air would be heated in an oil-fired heater located in a shelter above each of the three cells. The return air would be recirculated through the heater. A common fuel tank with an electric oil heater would be buried underground to supply all three heaters.

It is estimated that the capital costs associated with electrical heat tracing for all three dock cells would be in the order of $100,000. This would include construction and installation, and heat tracing cable costs. The capital


WET SIDE
HEAT TRACING CABLE
INSULATION
GRAVEL FILL

ELECTRICAL HEAT TRACING


WATER
AIR DUCT
INSULATION
A
A
GRAVEL
HEATING UNIT

VIEW A - A

HOT AIR HEATING

FIG. 8-6

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL FOR ARCTIC PORTS AND HARBOURS
ACRES

HEATING ARRANGEMENTS FOR THE NANISIVIK DOCK costs for a hot air heating system would be about $220,000 which would cover the cost of construction and installation, steel fabrication, three oil-fired heaters, and fuel tank. The annual operating costs for the electrical system are estimated to be $75,000 which includes electrical energy costs at $0.25/kW·h. The operating costs of the hot air heating system are estimated to be $35,000/yr based on a consumption of 50 000 L of fuel oil at $0.60/L.

The electrical heating system is attractive for its simlicity in installation and lower capital costs. However, the operating costs are higher due to the high cost of generating electricity in the Arctic. The hot air system, on the other hand, can be equally effective and has lower operating costs. The capital costs of installing a hot air system are larger, however, and in addition, there could be problems with water leaking through to flood the air duct, so that its reliability may be lower than the electrical heating arrangement.

### Mechanical Cutting and Removal

The physical cutting of the ice in front of the dock is a technique that could work. If the common manually-operated chain saws were used, the ice would have to be cut midway through the winter. Cutting would have to be combined with removal, of course, and a crane or large backhoe would be required for this. It is possible that a unit like the self-propelled mechanical ice cutters described previously could also be used. The design of the unit would depend on how often the ice was cut during the winter. A cutter similar to the Soviet unit, which is a combination of AST and cutter, would probably be more appropriate than the hull-shaped cutter tested in the United States.

If the objective is to cut and remove the ice only once and that, immediately before the shipping season begins, saws with at least a 5-m reach would be required. As far as is known, the longest blade used to cut ice was a coal chain saw of length 4.9 m as described in Section 4.4.2. However, even if such thick ice were cut, the problem of removing it could be formidable and, for that reason, it would be more reasonable to first cut and remove the ice during the middle of the winter when the thickness is more manageable. Ice of 2-m thickness has been cut and removed previously in the Arctic by using chain saws, ditching equipment and a crane. In constructing the dock at Nanisivik, ice was cut by using a ditcher and was then removed with a clam bucket mounted on a 55-tonne crane (Girgrah and Shah, 1977). It is thus feasible to remove the ice in the berthing area by similar means. The crane could operate from the dock itself thus eliminating the safety consideration with regard to the bearing capacity of the ice.

A very preliminary estimate based on a cutting rate of 1.5 m/min, a 2-m thick zone of ice 100 m by 10 m and blocks of ice 2 m by 2 m in area indicates a cutting time of less than 24 hours.

Considering the total operation of cutting and lifting, some of which can be done simultaneously, the overall removal time should be not more than a few days. Overall costs will depend largely on whether equipment has to be moved to the area or whether it can be rented locally. If the latter, the total costs should be less than $50,000.

### Explosives

Under certain circumstances, explosives could have some application to the ice problem at Nanisivik. However, if they were to be used only at the end of winter, the ice growth at the dock would in all likelihood be too massive to be broken by underwater charges. Even if it could the weight of charge required could leave the dock vulnerable to damage. It seems, therefore, that they would have to be used first earlier in the winter when the ice is thinner. However, the explosives would simply break the ice and the total ice accumulation at the dock by the end of winter even with multiple explosions could still be quite massive. This means that the ice would have to be removed once it is broken. Removal of the ice pieces produced by the explosion would probably be more difficult and time consuming, however, than lifting out large blocks of ice that has been cut by saws in a regular fashion. It, therefore, seems that explosives would not be an appropriate solution to either minimizing or removing the large ice buildup occurring in the berthing area. They could, however, have some use as a means of breaking up the thinner ice cover away from the berthing area thereby reducing the resistance on a vessel approaching the dock and providing a weak zone into which the ice in the berthing area could be displaced.

### Summary

Of the ice control techniques considered, a heating system incorporated into the sheet-pile cells appears to be the most feasible. This method is very effective since it prevents ice from forming on the cells in the first place. It is attractive as a long-term solution since, once the installation is complete, very little effort is required to maintain it. Construction and installation methods are straightforward and some precedence with heating arrangements has already been established in southern Canada.

While cutting and removing the ice may appear to be less costly, it entails mobilizing labour and equipment probably at least twice per winter. The logistics and long-term cost associated with this method make it unattractive.

Of the other possible solutions, thermal discharge could be a viable solution, particularly since the energy requirements are reasonable as it would operate only a short time prior to the opening of the shipping season. However, the lack of experience with such a system together with potential installation, maintenance and operational problems contribute to a reasonable degree of uncertainty with the technique.

Floats and pontoons would probably be effective in preventing ice formation on the cells and, being passive devices, would require no power to operate. However, their capital costs are sufficiently high to cause them to be rather unattractive solutions. They may have some merit, however, when considering berthing at the dock since a continuous dock surface would facilitate berthing, particularly if the vessel did not have tug support.

# 9. RECOMMENDATIONS FOR DATA COLLECTION

The following recommendations pertain to the type of information required in order to design ice control systems for Arctic locations. In many of the possible locations for future ports and harbours, the data that are required for such designs are simply not available. In such cases, extrapolations have to be made from the nearest location with records.

Any site which is being considered for future operation should be investigated in detail over at least one winter, and, for some parameters such as winds, much longer records are desirable. The following paragraphs outline the environmental information that should be gathered to aid in evaluating ice control systems. When carrying out such an evaluation, these data would have to be considered in combination with dock designs and the planned operation of the port.

The collection of such information is a first step to designing an appropriate ice control scheme for a particular location. As the design progresses, it may be valuable to conduct small-scale in situ tests or model tests to better determine the performance of a technique.

## 9.1 Meteorology

The principal meteorological parameters to be considered are air temperature, wind speed and direction, and precipitation--particularly snowfall, and solar radiation. Air temperature recorded over several winter seasons would enable a reasonable estimate to be made of the freezing degree-days for a site. This would in turn allow for ice thickness calculations to be made. Wind speed and direction will provide insight on possible ice movements and on preferred dock orientation. Information on snowfall and solar radiation would allow for a better evaluation of the performance of certain ice control systems.

## 9.2 Ice

Ice thickness measurements at the proposed site are desirable. Without such measurements, it is necessary to resort to a theoretical determination of the thickness by using the freezing degree-day record, which while providing in general, reasonable predictions, does not account for any site peculiarities that might cause the actual thickness to be different.

Observations and documentation of ice formation and movement during freeze-up and breakup are important as are the formation of pressure ridges, tidal cracks and other phenomena related to ice movement. As input to the design of structures for the site, data on the mechanical properties of the ice would be very useful.

### 9.3 Oceanography

A knowledge of the tides and currents at a site is necessary in order to realistically assess any ice control system. The effects of these parameters on ice growth and movement are important to the overall effectiveness of an installation and these should be clearly understood. A knowledge of the currents at freeze-up and breakup is important--particularly so, if ice movement is affected by river inflow.

Water temperature and salinity profiles should be made in a potential harbour location as these could determine the effectiveness of certain ice control systems. This is particularly the case with air bubblers. The temperature structure of any nearby ponds or lakes should also be investigated to determine whether they could be used to control ice growth in the harbour.

In addition to these environmental parameters, the design of any ice control system must also take into account the design of the dock, the intended operation of the port, the expected ship frequency and the general characteristics of the vessels that will use the harbour. All information relating to these design parameters should be clearly understood when evaluating control techniques as they will eventually determine the type of system implemented.

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# APPENDIX A

# DESIGN PARAMETERS FOR SELECTED PORTS AND HARBOURS

## LIST OF PORTS AND HARBOURS SELECTED

| Name | Location |
|---|---|
| **Arctic Sites** | |
| Bridport Inlet | 75°02'N, 108°44'W |
| Cambridge Bay | 69°07'N, 105°03'W |
| Frobisher Bay | 61°56'N, 65°08'W |
| McKinley Bay | 69°57'N, 131°27'W |
| Nanisivik | 73°14'N, 85°10'W |
| Little Cornwallis Island | 75°23'N, 96°53'W |
| Rea Point | 75°04'N, 105°56'W |
| Resolute Bay | 74°39'N, 94°47'W |
| Sachs Harbour | 71°59'N, 125°14'W |
| Tuktoyaktuk | 69°27'N, 133°00'W |
| **Non-Arctic Sites** | |
| Churchill, Manitoba | 58°47'N, 94°12'W |
| Northwest Point, Lake Melville | 59°30'N, 53°40'W |
| Thunder Bay | 48°25'N, 89°13'W |

**Name of Port/Harbour:** BRIDPORT INLET

**Location:** 75°02'N, 108°44'W (South coast of Melville Island)

## Climate

(Based on Rea Point data.)

| | | |
|---|---|---|
| mean annual temperature | -17°C | 1969 to 1972 |
| minimum mean daily temperature | -21.3°C | |
| maximum mean daily temperature | -15.1°C | |
| extreme minimum temperature | -45°C | |
| extreme maximum temperature | +11°C | |
| mean freezing degree-days | 6,566 | 1951 to 1980 |
| mean melting degree-days | 222 | |
| average wind velocity | 5.4 m/s | |
| extreme wind velocity | 30.3 m/s | |
| predominant wind direction (annual) | NW | |
| summer | S | |
| fall | NW | |
| winter | NW | |
| spring | NW | |
| mean annual total precipitation | 100 mm | |
| mean annual total snowfall | 600 mm | |
| mean total snow cover | 230 mm | |
| mean winter maximum snow cover depth | 254 mm | |

## Bathymetry and Topography

Bridport Inlet - semicircular in shape with a total area of 93 km$^2$ and maximum dimensions of 9.3 km north-south, and 14.6 km along a general east-west direction. The inlet is bounded to the south by a narrow low-lying peninsula which projects 8.2 km in a west-northwest direction from the southeast corner of the inlet, leaving an entrance of about 3 km wide.

Inside the inlet, depths on approach to proposed LNG terminal exceed 100 m. Approximately 1.6 km from the north shore, they shelve gradually to 30 m about 0.4 km offshore. Depths of 17 m lie in the central part of the inlet 3.7 km northeast of the east entrance point and extend to the south shore. Large sand and gravel banks with depths less than 1 m lie 0.8 km offshore near the Mecham River delta.

The west half of the inlet has deep water in excess of 100 m and a maximum depth of 144 m. A ridge extends north-south separating the two halves of the inlet.

The east basin is from 50 - 70 m deep. A narrow channel cuts through the ridge a little north of the centre with minimum depths of 58 m. The ridge then carries on in a northwest direction, culminating in a shoal with a minimum water depth of 1.5 m.

-The shoal is separated from the northern shoreline by a narrow and relatively deep channel of 20- to 30-m depth.

-The 20-m contour is approximately 500 - 1,000 m off the low water shoreline; exceptions--on the western and northern shores where the 20-m mark is 1,200 - 1,500 m into the channel from the east side and 25 m from the west side. Therefore, for navigation purposes, the entrance narrows from 3,000 - 1,650 m; if a 30-m contour is used, the entrance is approximately 1,450 m in width.

-The surrounding topography is relatively low-lying and the bay is sheltered.

-The inlet is bound to the north by a range of hills, rising abruptly from a narrow beach region to el 150 m.

-In the northwest corner of the inlet, the Mecham River has cut a broad valley to form a sandy floodplain and a large delta region.

-The west side of the bay has an extensive flat, marshy area rising in elevation to a range of hills 300 m high, 5 km inland. The east sandstone plateau is approximately 50 m high.

## Oceanography

| | |
|---|---|
| mean tide range | 0.9 m |
| minimum tide range | 0.3 m |
| large tide range | 1.6 m |
| maximum tide range (19-yr return period) | 2.1 m |
| mean surface current | 5 cm/s |
| maximum surface current | 7 cm/s |
| significant wave height (100-yr return period) | 4.0 m (period - 7.5 s) |
| mean water temperature (winter, fall, spring) | -1.78°C |
| mean salinity (winter) | 32.3 pro mille |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 2.1 m |
| time of ice formation | mid-Sept (remains mobile for 1 or 2 weeks before freezing solid) |
| time of ice breakup | last week in July or first week in Aug (inlet usualy completely clear in mid-Aug) |

## Bottom Conditions

The site overburden has an average thickness of 8.5 m varying from 3 - 18 m.

-Consists of very softsilt and clay deposits (1.5 - 4.5 m thick) overlying till-like deposits of sands and gravels in a dominating matrix of silts and clays (2 - 12 m thick).

-These deposits mantle a fine- to medium-grained gravel sandstone which is frequently highly fractured and contains siltstone interbeddings.

-Complete stratigraphic sequence can be classified on the basis of temperature as permafrost, but only the lower portion of the till-like deposit and the sandstone contain ice inclusions, which range in size from pore crystals to 5-m thick lenses.

-The upper 6 m (approximately) of the till-like deposit and all of the soft silt and clay layers are unbonded (with no pore ice).

-The high salinity of the pore fluid is felt to be the reason for the lack of visible ice in the surficial deposits.

## Dock Characteristics

Proposed LNG dock is 450 m long and 35 m wide supported by caissons and columns 2-m in diameter and at 43.5-m centres. Dock is to have continuous fender to allow vessels to slide along the dock while pushing ice under the dock where it will be melted by waste heat from the liquefaction process.

Name of Port/Harbour: **CAMBRIDGE BAY**

Location: 69°07'N, 105°03'W (Victoria Island)

## Climate

| | |
|---|---|
| mean annual temperature | -14.9°C |
| minimum mean daily temperature | -18.4°C |
| maximum mean daily temperature | +17°C |
| extreme minimum temperature | -52.8°C |
| extreme maximum temperature | +28.9°C |
| | |
| mean freezing degree-days | 6,028 |
| mean melting degree-days | 580 |
| | |
| average wind velocity | 5.7 m/s (1953 to 1972) |
| extreme wind velocity | 24.7 m/s |
| predominant wind direction (annual) | NW |
| summer | N to NE |
| fall | NW |
| winter | NWW |
| spring | NW |
| | |
| mean annual total precipitation | 137 mm |
| mean annual total snowfall | 727 mm |
| mean winter maximum snow cover depth | 457 mm |

## Bathymetry and Topography

Depths range from 8.2 - 35 m with many shoals.

## Oceanography

| | |
|---|---|
| mean tide range | 0.4 m |
| minimum tide range | - |
| large tide range | 0.5 m |
| maximum tide range | 1.6 m |
| | |
| mean surface current | - |
| maximum surface current | 0.5 m/s |
| | |
| maximum significant wave height | - |
| | |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 2.2 m |
| time of ice formation | late Sept |
| time of ice breakup | mid-June to mid-July |

## Bottom Conditions

-

## Dock Characteristics

T-shaped public wharf--minimum depth alongside of 4.9 m.

Name of Port/Harbour: **FROBISHER BAY**

Location: 61°56'N, 65°08'W

-Main entrance between Black Bluff on Edgall Island and Queen Elizabeth Foreland of Loks Land, 53 km to the north-northeast.

-Alternative entrances are Gabriel Strait on the east side and Annopolis Strait on the northwest side of Lower Savage Islands.

## Climate

| | | |
|---|---|---|
| mean annual temperature | -0.9°C | 1941 to 1970 |
| minimum mean daily temperature | -30.1°C | |
| maximum mean daily temperature | -5.2°C | |
| extreme minimum temperature | -45.6°C | |
| extreme maximum temperature | +24.4°C | |

| | |
|---|---|
| mean freezing degree-days | 4,015 |
| mean melting degree-days | 1,189 |

| | | |
|---|---|---|
| average wind velocity | 4.6 m/s | |
| extreme wind velocity | 35.8 m/s (13-yr record) NW direction | |
| predominant wind direction (annual) | NW | |
| summer | NNW [variable] | 1941 to 1970 |
| fall | NW | |
| winter | NW (W) | |
| spring | NW (WN) | |

| | | |
|---|---|---|
| mean annual total precipitation | 415.0 mm | 1941 to 1970 |
| mean annual total snowfall | 2,469 mm | |
| mean winter maximum snow cover depth | 533 mm | |

## Bathymetry and Topography

### (a) Depths

-In general, midchannel depths in the outer part of the bay are great.

-A deep trough extends along the southwest side from a threshold at the entrance to the bay to the islands which separate the inner and outer parts.

-A shelf with depths of under 37 m (20 fathoms) up to 19.3 km offshore lies along the northeast shore of the outer bay.

-Little of the northeast side of the outer bay has been sounded.

-A number of channels and passages run through the islands. Of these, Pike-Resor Channel is the most suitable for deep-draught vessels, having navigational aids and being free of ice before the others.

-Both shores of Frobisher Bay, almost as far as its head, are rugged and mountainous; southwestern shore is the higher and bolder with steep cliffs rising in places 304.8 m or more from the sea, backed by mountains with elevations of 609.6 - 914.4 m.

-Few raised beaches, but most of the alluvium is under water at high tide; mud flats at low water.

-Inland from the coasts, land is more mountainous, rock basin lakes very numerous and there are several small mountain glaciers.

-Two permanent ice caps; namely, Grinnel Glacier and Terra Nivea Ice Cap.

## Oceanography

| | |
|---|---|
| mean tide range | 7.8 m (at Koojesse Inlet) |
| minimum tide range | - |
| large tide range | 11.1 m (at Koojesse Inlet) |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | 3.5 m/s |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.7 m |
| time of ice formation | Sept 20 to Nov 1 |
| time of ice breakup | May 22 to July 7 |

## Bottom Conditions

-

## Dock Characteristics

There is no dock in Frobisher Bay. A landing beach, about 91.4 m wide and composed of hard rock, shale, mud and sand, with a gradient of about 1:150, has been sufficiently cleared of boulders and graded to allow ships to beach to discharge and load, or for repairs; the Ministry of Transport bases three LCM's and three dumb barges here.

Name of Port/Harbour: **McKINLEY BAY**

Location: 69°57'N, 131°27'W

## Climate

(Based on Tuktoyaktuk data.)

| | |
|---|---|
| mean annual temperature | -10.7°C |
| minimum mean daily temperature | -14.2°C |
| maximum mean daily temperature | -7.2°C |
| extreme minimum temperature | -50°C |
| extreme maximum temperature | +30°C |
| mean freezing degree-days | 4,500 |
| mean melting degree-days | 900 |
| average wind velocity (annual) | 4.8 m/s |
| extreme wind velocity | 24.2 m/s (10-yr record) |
| predominant wind direction (annual) | E |
| summer | SE (E) |
| fall | E |
| winter | W (SE) |
| spring | E (NE) |
| mean annual total precipitation | 129.6 mm |
| mean annual total snowfall | 567 mm |
| mean winter maximum snow cover depth | - |

## Bathymetry and Topography

General depths between 3.4 and 6 m. The bay is bordered on its east side by a 14-km long sand spit. An abandoned artificial island 8 km northeast of Atkinson Point was under 1 m of water in 1979, is unmarked, and is a danger to navigation.

## Oceanography

| | |
|---|---|
| mean tide range | 0.3 m |
| minimum tide range | - |
| large tide range | 0.5 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.7 m |
| time of ice formation | late Sept |
| time of ice breakup | mid-June |

### Bottom Conditions

-

### Dock Characteristics

No dock exists in McKinley Bay; the bay is used by Dome Petroleum Limited as a winter mooring basin for its drilling fleet.

Name of Port/Harbour: **NANISIVIK**

Location: 73°14'N, 85°10'W (South side of Strathcona Sound)

## Climate

(Based on Arctic Bay data.)

| | | |
|---|---|---|
| mean annual temperature | -13.7°C | 1941 to 1970 |
| minimum mean daily temperature | -17.2°C | |
| maximum mean daily temperature | -9.5°C | |
| extreme minimum temperature | -53°C | |
| extreme maximum temperature | +22.2°C | |
| mean freezing degree-days | 5,500 | |
| mean melting degree-days | 370 | |
| average wind velocity | 2.2 m/s | |
| extreme wind velocity | 21.1 m/s | |
| predominant wind direction (annual) | NW | |
| summer | NW | |
| fall | NNW | |
| winter | N and S | |
| spring | NNW | |
| mean annual total precipitation | 125.7 mm | |
| mean annual total snowfall | 711 mm | |
| mean winter maximum snow cover depth | 356 mm | |

## Bathymetry and Topography

Shoal area lies just west of the wharf.

## Oceanography

| | |
|---|---|
| mean tide range | 1.5 m |
| minimum tide range | - |
| large tide range | 2.5 m |
| maximum tide range | - |
| mean surface current | 0.25 m/s |
| maximum surface current | - |
| maximum significant wave height | 2.4 m |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.7 m |
| time of ice formation | late Sept/early Oct |
| time of ice breakup | May 30 to July 26 |

### Bottom Conditions

-

### Dock Characteristics

The wharf consists of three sheet-steel cells 23-m diam filled with gravel and faced with heavy tires. The wharf deck and causeway connecting it to the shore are filled with gravel. The wharf is about 100 m long and has a least chartered depth of 9.1 m alongside.

Name of Port/Harbour: **LITTLE CORNWALLIS ISLAND**

Location: 75°23'N, 96°53'W

## Climate

(Based on Resolute data.)

| | | |
|---|---|---|
| mean annual temperature | -16.4°C | ) |
| minimum mean daily temperature | -19.6°C | ) |
| maximum mean daily temperature | -13.3°C | ) 1941 to |
| extreme minimum temperature | -52.2°C | ) 1970 |
| extreme maximum temperature | +18.3°C | ) |
| mean freezing degree-days | 6,267 | |
| mean melting degree-days | 250 | |
| average wind velocity | 5.8 m/s (1963 to 1972) | |
| extreme wind velocity | 27.8 m/s | |
| predominant wind direction (annual) | NW | |
| summer | NW, SE | |
| fall | N to NW | |
| winter | NW | |
| spring | NW | |
| mean annual total precipitation | 136.4 mm | |
| mean annual total snowfall | 787 mm | |
| mean winter maximum snow cover depth | 356 mm | |

## Bathymetry and Topography

-

## Oceanography

| | |
|---|---|
| mean tide range | - |
| minimum tide range | - |
| large tide range | - |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.9 m |
| time of ice formation | mid-Sept to early Oct |
| time of ice breakup | mid-July to early Aug |

## Bottom Conditions

-

## Dock Characteristics

The dock consists of steel sheet-pile construction with back-filled interconnecting cells and is approximately 113 m long, and extends 122 m from shore.

Name of Port/Harbour: **REA POINT** (Melville Island)

Location: approximately 75°04'N, 105°56'W (Rea Point Cove lying 2.8 km north of Consett Head)

## Climate

(Based on Mould Bay data.)

| | | |
|---|---|---|
| mean annual temperature | -18.2°C | |
| minimum mean daily temperature | -38.7°C | |
| maximum mean daily temperature | +7.2°C | |
| extreme minimum temperature | -50.6°C | ) 1969 to |
| extreme maximum temperature | +16.7°C | ) 1972 |
| mean freezing degree-days | 6,566 | |
| mean melting degree-days | 222 | |
| average wind velocity | 5 m/s | |
| extreme wind velocity | 27 m/s (1969 to 1972) | |
| predominant wind direction (annual) | NNW | |
| summer | NNW | |
| fall | WNW | |
| winter | WNW | |
| spring | NW | |
| mean annual total precipitation | 94.5 mm | ) 1969 to |
| mean annual total snowfall | 467 mm | ) 1972 |
| mean winter maximum snow cover depth | 254 mm | |

## Bathymetry and Topography

Rea Point Cove - 0.8 km wide and indents the coast for 0.8 km; land around the cove is quite low, rising gradually inland.

Rea Point - a low point of deltaic origin with a sand and clay beach extending inland for 0.8 km, part of which may be covered at times.

Depths of Byam Channel - west side; depths in the cove shoal gradually to the landing beach; on the line of the beacons, depths of 18 m (10 fathoms) exist at the entrance, with 9 m (5 fathoms) near the landing beach; the deepest water lies close to the north shore, where depths of 7.9 m may be found at a distance of 30 m off the landing beach.

## Oceanography

| | |
|---|---|
| mean tide range | 0.8 m |
| minimum tide range | - |
| large tide range | 1.3 m |

| | |
|---|---|
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 2.1 m |
| time of ice formation | mid-Sept to early Oct |
| time of ice breakup | mid-Aug |

### Bottom Conditions

-deltaic origin.

### Dock Characteristics

No dock exists at Rea Point; a landing beach is situated 0.4 km west of Birch Point, having a length of 0.24 km and a breadth of about 0.2 km.

In 1969, a temporary wharf in the form of a 61-m long barge with a ramp provided a depth of 7 m alongside.

Name of Port/Harbour: **RESOLUTE BAY**

Location: 74°39'N, 94°47'W (between Prospect Point and Sight Point, 3.2 km northwest)

## Climate

| | | |
|---|---|---|
| mean annual temperature | -16.4°C | ) |
| minimum mean daily temperature | -19.6°C | ) |
| maximum mean daily temperature | -13.3°C | ) 1941 to |
| extreme minimum temperature | -52.2°C | ) 1970 |
| extreme maximum temperature | +18.3°C | ) |
| mean freezing degree-days | 6,267 | |
| mean melting degree-days | 250 | |
| average wind velocity | 5.8 m/s | |
| extreme wind velocity | 27.8 m/s (25-yr return) | |
| predominant wind direction (annual) | NW | ) |
| summer | NW, SE | ) |
| fall | N to NW | ) 1955 to |
| winter | NW | ) 1972 |
| spring | NW | ) |
| mean annual total precipitation | 136.4 mm | ) 1941 to |
| mean annual total snowfall | 787 mm | ) 1970 |
| mean winter maximum snow cover depth | 356 mm | |

## Bathymetry and Topography

-Low shale beaches with higher land rising gradually behind.

-Shores generally low.

-Mecham River flows into the northeast part of the bay.

-Resolute Creek, which drains Resolute Lake, flows into the west part.

-Signal Hill, el 194 m, rises about 1 km north of the head of the bay.

Shoals encumber the full width of the entrance and outer part of Resolute Bay, and strict adherenece to the ranges is necessary.

-No dredged channel and no dredging is done to maintain least depths along the ranges.

-Ships drawing more than 8.5-m anchor in 27.4 - 31 m (15 - 17 fathoms) 1.6 km south of Sight Point.

-Ships drawing less than 8.5-m anchor in 18 - 27 m (10 - 15 fathoms) in the central and north part of the bay.

Oceanography

| | |
|---|---|
| mean tide range | 1.8 m |
| minimum tide range | - |
| large tide range | 2.9 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature with depth (winter) | - |
| mean salinity with depth (winter) | - |

Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.9 m |
| time of ice formation | mid-Sept to early Oct |
| time of ice breakup | mid-July to early Aug |

-After August, ice conditions in the bay depend on wind direction; the bay becomes blocked in extended periods of west winds, and becomes ice-free in prevailing northeast and easterly winds. Thus, landing operations may be curtailed by ice at any time. The last icebreaker normally leaves late in September.

Bottom Conditions

-Anchorages are poor in mud and shale, and vessels have dragged in strong winds.

Dock Characteristics

No dock exists at Resolute Bay.

There are two landing beaches, one, known as MOT Beach, located on the west side of the bay, has two gravel jetties about 46 m long.

-The second beach, known as North Beach, is situated close southwest of the front beacon of the three which in line bear 353-1/2 deg.

A Pier - constructed by Narwhal Arctic Services on the east side of the bay about 1.3 km east-northeast of MOT Beach was destroyed by ice in 1977--in its place, a gravel ramp was built, dumb barges were placed at the outer end of the ramp, and a vessel drawing 7.6 m berthed on the barges.

**Name of Port/Harbour:** **SACHS HARBOUR** (Banks Island)

**Location:** 71°59'N, 125°14'W

## Climate

| | | |
|---|---|---|
| mean annual temperature | -13.7°C | ) |
| minimum mean daily temperature | -16.9°C | ) |
| maximum mean daily temperature | -10.5°C | ) 1941 to |
| extreme minimum temperature | -49.4°C | ) 1970 |
| extreme maximum temperature | +21.1°C | ) |
| mean freezing degree-days | 5,525 | |
| mean melting degree-days | 418 | |
| average wind velocity | 5.7 m/s (summer) | |
| extreme wind velocity | 26.9 m/s (12-yr record)<br>NE direction | |
| predominant wind direction (annual) | SE | |
| summer | SE | |
| fall | E | |
| winter | SE | |
| spring | SE | |
| mean annual total precipitation | 102.5 mm | ) 1941 to |
| mean annual total snowfall | 580 mm | ) 1970 |
| mean total snow cover | 635 mm | |

## Bathymetry and Topography

A shoal spit, on which the sea breaks, extends 1.6 km east-southeast from its northwest entrance point; another shoal spit, with less than 2 m over it, extends 0.8 km west-northwest from its southeast entrance point. A bar connects these two spits; the channel across this bar was 0.97 km wide with a depth of 3 m over it in 1972.

## Oceanography

| | |
|---|---|
| mean tide range | 0.2 m |
| minimum tide range | - |
| large tide range | 0.3 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.7 m |
| time of ice formation | early Oct (complete ice cover by middle of the month) |
| time of ice breakup | mid-June (clear by middle of July) |

### Bottom Conditions

-

### Dock Characteristics

Landing Beach - vessels drawing 1.8 m are able to come alongside near the tip of the point at the settlement, 0.32 km south of the beacon range.

Name of Port/Harbour: **TUKTOYAKTUK**

Location: 69°27'N, 133°00'W (MacKenzie River delta)

## Climate

| | |
|---|---|
| mean annual temperature | -10.7°C |
| minimum mean daily temperature | -14.2°C |
| maximum mean daily temperature | -7.2°C |
| extreme minimum temperature | -50°C |
| extreme maximum temperature | +30°C |
| mean freezing degree-days | 4,500 |
| mean melting degree-days | 900 |
| average wind velocity (annual) | 4.8 m/s |
| extreme wind velocity | 24.2 m/s (10-yr record) |
| predominant wind direction (annual) | E |
| summer | SE (E) |
| fall | E |
| winter | W (SE) |
| spring | E (NE) |
| mean annual total precipitation | 129.6 mm |
| mean annual total snowfall | 567 mm |
| mean total snow cover | 533 mm |

## Bathymetry and Topography

-

## Oceanography

| | |
|---|---|
| mean tide range | 0.3 m |
| minimum tide range | - |
| large tide range | 0.5 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.7 m |
| time of ice formation | late Sept to mid-Oct |
| time of ice breakup | mid- to late June |

## Bottom Conditions

-

## Dock Characteristics

Public and commercial wharves have depths alongside varying between 2.1 and 6.1 m. Mooring buoys can accommodate vessels up to 122 m in length. Repair facilities, including a floating dock, are available by prior arrangement.

Name of Port/Harbour: **CHURCHILL, Manitoba**

Location: 58°47'N, 94°12'W

### Climate

| | | |
|---|---|---|
| mean annual temperature | -7.3°C | 1943 to 1972 |
| minimum mean daily temperature | -24.3°C | |
| maximum mean daily temperature | -3.3°C | |
| extreme minimum temperature | -45°C | |
| extreme maximum temperature | +32.8°C | |

| | |
|---|---|
| mean freezing degree-days | 3,752 |
| mean melting degree-days | 1,100 |
| average wind velocity | 6.4 m/s |
| extreme wind velocity | 32.2 m/s (1955 to 1980) |
| predominant wind direction (annual) | NW |
| summer | N to E, NW |
| fall | W to NW |
| winter | W to NW |
| spring | N, NW |
| mean annual total precipitation | 397 mm |
| mean annual total snowfall | 1,755 mm |
| mean winter maximum snow cover depth | 711 mm |

### Bathymetry and Topography

-

### Oceanography

| | |
|---|---|
| mean tide range | 3.4 m |
| minimum tide range | - |
| large tide range | 4.6 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 1.6 m |
| time of ice formation | late Oct to mid-Nov |
| time of ice breakup | early June |

## Bottom Conditions

The bottom material varies between large boulders and fine sand.

## Dock Characteristics

The dock is a wood crib wharf 838 m long and constructed from 30-cm by 30-cm timbers faced with 10-cm by 30-cm lining planks.

Name of Port/Harbour: **NORTHWEST POINT**, Lake Melville,
Labrador

Location: 59°30'N, 53°40'W

## Climate

(Based on Goose Bay data.)

| | | |
|---|---|---|
| mean annual temperature | 0°C | 1941 to 1970 |
| minimum mean daily temperature | -5°C | |
| maximum mean daily temperature | +4.6°C | |
| extreme minimum temperature | -39°C | |
| extreme maximum temperature | +37.8°C | |

| | |
|---|---|
| mean freezing degree-days | 1,712 |
| mean melting degree-days | 1,813 |
| average wind velocity | 4.4 m/s |
| extreme wind velocity | 23.7 m/s |
| predominant wind direction (annual) | W |
| summer | NE to WSW |
| fall | W (WSW) |
| winter | WSW |
| spring | NE |
| mean annual total precipitation | 877 mm |
| mean annual total snowfall | 400 mm |
| mean winter maximum snow cover depth | 711 mm |

## Bathymetry and Topography

The site for the proposed harbour is located on a curved sandy shore on a crescent-shaped coastline between Northwest Point and Northwest River. The 6-m contour of Lake Melville runs approximately parallel to the shoreline at the proposed site about 1/2 km offshore. The 21-m and 12-m contours are 200 m and 150 m respectively from the shoreline.

## Oceanography

| | |
|---|---|
| mean tide range | 0.4 m |
| minimum tide range | - |
| large tide range | 0.6 m |
| maximum tide range | - |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | 4 m |
| mean temperature with depth (winter) | - |
| mean salinity with depth (winter) | - |

### Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 0.86 m |
| time of ice formation | mid- to late Nov |
| time of ice breakup | late Apr to early May |

### Bottom Conditions

The bottom consists of very soft clayey silt with some sand seams to depths of at least 70 - 80 m.

### Dock Characteristics

A small timber crib wharf suitable for small craft is located on the west side of Northwest Point.

Name of Port/Harbour: **THUNDER BAY**

Location: 48°25'N, 89°13'W

## Climate

| | |
|---|---|
| mean annual temperature | +2.4°C |
| minimum mean daily temperature | -3.6°C |
| maximum mean daily temperature | +8.4°C |
| extreme minimum temperature | -41.1°C |
| extreme maximum temperature (1877 to 1981) | +40°C |
| mean freezing degree-days | 1,538 |
| mean melting degree-days | 2,410 |
| average wind velocity | 3.9 m/s |
| extreme wind velocity | 22.4 m/s |
| predominant wind direction (annual) | W |
| summer | W |
| fall | W |
| winter | W |
| spring | E |
| mean annual total precipitation | 738.5 mm |
| mean annual total snowfall | 2,211 mm |
| mean winter maximum snow cover depth | 787 mm |

## Bathymetry and Topography

Main areas are dredged to depths of 7.6 - 8.2 m, but are subject to silting.

## Oceanography

| | |
|---|---|
| mean tide range | na |
| minimum tide range | na |
| large tide range | na |
| maximum tide range | na |
| mean surface current | - |
| maximum surface current | - |
| maximum significant wave height | - |
| mean temperature (winter) | - |
| mean salinity (winter) | na |

## Ice

| | |
|---|---|
| maximum uniform mean ice thickness | 0.80 m |
| time of ice formation | late Nov to early Dec |
| time of ice breakup | early to mid-Apr |

### Bottom Conditions

-

### Dock Characteristics

Several general cargo wharves, 20-grain elevator wharves, ship repair facilities.

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# Volume

# 2

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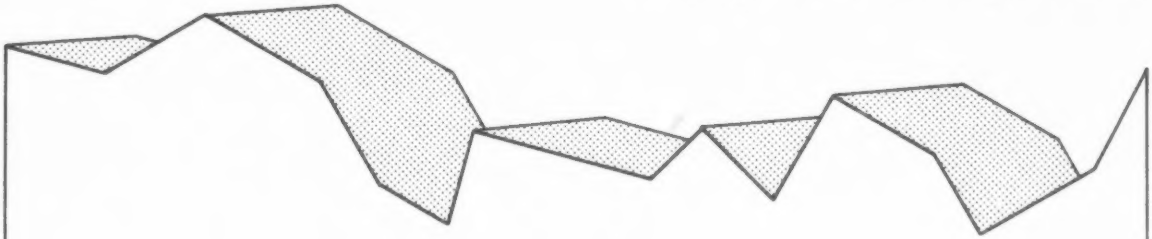

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17. Abstract

This report examines the types of ice problems that may occur in harbours that are operated in ice conditions and presents a description of a range of ice control techniques that could be used in conjunction with certain design approaches to mitigate these problems. Criteria for harbour design are addressed and a number of Arctic and non-Arctic locations are briefly described in order to illustrate the ice problems that are, or may be, experienced. Ice control techniques are evaluated for general application and a case study is conducted of the potential ice problems at Nanisivik, Baffin Island, to illustrate a procedure that could be followed in evaluating ice control techniques for a particular location. Recommendations for data collection to provide necessary design information are also made.

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17. Résumé

Ce rapport récapitule les différents types de problèmes que peut présenter l'accumulation des glaces dans les ports et décrit la gamme des techniques de lutte contre les glaces utilisables concurremment à une approche modifiée de la conception des ports. Il aborde les critères de conception portuaire, puis décrit un certain nombre de sites arctiques et autres, mettant en évidence les problèmes que les glaces peuvent y poser. Il fait une évaluation générale des techniques proposées et prend le port de Nanisivik dans l'île de Baffin comme cas d'espèce pour illustrer la procédure applicable en vue de choisir les techniques à mettre à oeuvre dans un cas particulier. Enfin, il fait des recommandations concernant la saisie des données nécessaires à l'étude proprement dite des techniques à utiliser.

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SUMMARY

The study shows that a considerable reduction of intrusion of salt water through navigation locks can be obtained by releasing bubbles of air from perforated pipes placed on the bottom of the lock chamber. The bubbles of air create an upward flow of water that reduces the intrusion of salt water, provided that sufficient air is supplied. A theory to determine the influence of the upward flow of water is developed. Theory and measurements made in difficult locks with depths of 5, 7.5, and 10 m agree favorably. The presented data can be used to determine the required quantity of air under variable operation conditions.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
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REFERENCE SUMMARY

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**SUMMARY**

Experiments with wave machines in water subjected to surface cooling are described.

It is found that wave action will provide water mixing and retard ice formation. Eventual ice formation takes the form of frazil ice and slush which congregates at the water surface. The growing slush layer is found to insulate underlying water against heat losses. Mass transportation of slush ice in the direction of wave propagation is proven.

The clearing of ice from harbour basins by artificial wave action is proposed and suitable wave machines for this purpose are discussed.

| KEYWORDS | CLASSIFICATION |
|---|---|
| flow developers | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Andersen, P. F.
"Ice Prevention in Waterways"
Foundation of Canada Engineering Corporation Limited
August 1963

**NO.**

AN 63

**SUMMARY**

Experiments aimed at finding suitable machinery for the purpose of maintaining ice-free navigation channels during the winter months are presented.

Methods of ice prevention have been divided into 4 main categories

-ice prevention by surface current
-ice prevention by forced convection
-ice prevention by wave action
-ice breaking and removal of broken ice.

**KEYWORDS**
ice removal, flow developers, icebreakers

**CLASSIFICATION**
Ice
Suppression
Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Andersen, P. F.<br>"Wave Machine Installations"<br>US Patent 3,477,233<br>1969 | AN 69 |

**SUMMARY**

The specification describes wave machines which are for use in keeping a harbour or channel free from ice. The wave machines float on the surface so that performance is not affected by changes in water level.

Andersen has found that wave action can break up an ice sheet when the wave height exceeds 4 or 5 times the thickness of the ice sheet. On a water surface covered with a pack of ice chunks, artificial wave action can prevent ice chunks from freezing together to form a continuous ice cover.

| KEYWORDS | CLASSIFICATION |
|---|---|
| flow developers | Ice<br>Suppression |

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Andersen, P. F.
"Surface Agitation in Ice Prone Waters"
6th International Conference on Port and Ocean
Engineering Under Arctic Conditions
pp 820 - 829
Quebec
July 27 - 31, 1981

**NO.**

AN 81

**SUMMARY**

The range from 1.5 - 2.5 seconds of period waves and ripples on the water surface are too small to deter navigational activities but large enough to affect ice happenings.

Mixing and mass transportation of surface waters inherent in wave action will retard initial ice formation, prevent coherent ice growth and move frazil ice formations and slush along the way of the wave travel.

Continuous clearing of ice from harbour basins and ferry landings etc by ceaseless wave generation have been proposed earlier. The disposal of slush ice outside of the harbour would depend on existing incomplete ice cover at sea or icebreaker activity.

The author and Kurt Larsen of Kurt Larsens Maskinfabrik ApS have developed and built floating ripple and wave generators, and their experiments confirm that a stationary machine can produce far-reaching wave action at low energy cost.

With reference to future Arctic ports, it is recommended that planning take into consideration the accommodation of stationary machines for ceaseless agitation as described to handle ice problems within the port area to complement icebreaker activities at sea.

**KEYWORDS**
flow developers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Ankers, J. W. and E. P. Antoniades
"Sulphur Foams for Permafrost Protection"
Ives, M. B. (ed) Materials Engineering in the
Arctic
Proc. of an International Conference
Quebec
September 27 - October 1, 1976

**NO.**

AN 76

**SUMMARY**

A test section of sulphur foam as road insulation was successfully installed in August 1974 on Dempster Highway near the MacKenzie delta. Foam made on-site in a mobile pilot plant was applied at the rate of 45 kg/min on top of 0.45 m of granular fill. The resulting pad, 40 m long, 14 m wide, and 110 mm thick, was covered with more fill to a final grade of 1.5 m above original ground.

Monthly temperature data showed no evidence of thermal conductivity changes and samples removed after one year contained only 0.16 vol percent water. The amount of insulation used for summer installation was not enough to regenerate permafrost permanently within a year. It was calculated that the insulation would have been enough for winter installation on permafrost of higher ice content (30 - 50 percent).

**KEYWORDS**

insulation

**CLASSIFICATION**

Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Argiroff, C.
"Planning the Great Lakes - St. Lawrence Seaway
Navigation Season Extension Program"
3rd International Symposium on Ice Problems
Hanover, New Hampshire
1975

**NO.**

AR 75

**SUMMARY**

The demonstration activities and studies conducted to date have proven that extending the navigation season on the Great Lakes - St. Lawrence Seaway System is technically feasible.

The successful tests conducted as part of the ice management and control functional work groups are of interest. The bubbler tests conducted for two successive years in a navigation channel in the St. Mary's River proved that ice thickness could be reduced. Bubbler tests in Duluth Harbor and Superior Harbor were also successful. Effectiveness of bubblers in open lake conditions under a shifting ice field still remains to be demonstrated.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Ashton, G. D.<br>"Use of Air Bubbler Systems to Suppress Ice"<br>USA CRREL, Special Report 210<br>September 1974 | AS 74 |

**SUMMARY**

Two-dimensional line source bubbler systems used to induce convective melting of the undersurface of an ice cover are analyzed and a procedure developed for predicting the effectiveness of such a system. Various field conditions are considered and limitations to effectiveness pointed out. Example applications of the concepts and the procedures are illustrated in Appendixes.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Ashton, G. D.
"Experimental Evaluation of Bubbler-Induced Heat Transfer Coefficients"
3rd International Symposium on Ice Problems
Hanover, New Hampshire
1975

**NO.**

AS 75

**SUMMARY**

The results of laboratory experiments to evaluate the heat transfer coefficients associated with flow induced by a line source bubbler system are reported. The heat transfer coefficients, both in the impingement area and laterally outward from the axis of the impingement region, were evaluated by observation of melting rates induced at the underside of an ice cover formed in a large cold room. The experimental results are compared and interpreted in light of an analytical model previously developed. Implications for field applications of bubbler systems are discussed.

**KEYWORDS**

air bubblers

**CLASSIFICATION**

Ice
Suppression

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Ashton, G. D.
"Numerical Simulation of Air Bubbler Systems"
Canadian Journal Civil Engineering
Vol 5, pp 231 - 238
1978

**NO.**

AS 78

**SUMMARY**

The use of air bubbler systems to suppress ice formation is a technique that has been applied in a variety of situations with varying degrees of success. In 1974, two-dimensional line source bubbler systems were analyzed by G. D. Ashton in an effort to make available a tool that may be used in the design of a bubbler installation. That analysis was a steady-state evaluation of the melting rate of an ice cover above a bubbler system predicted on the basis of the input variables (depth, air discharge rate, water temperature). In actual operation, however, a bubbler "sees" changing conditions such as diurnal and longer-term weather conditions, varying water temperatures and depletion of the available thermal reserve.

The simulation presented uses the steady-state analysis developed earlier by Ashton and steps it in time with each new condition determined from the results of the previous time step. In this sense, the analysis may be considered quasi-steady.

Results of the simulation are presented for a winter in Superior, Wisconsin, and illustrate the variation in width of open water area with changing weather conditions with good comparison to field observations.

**KEYWORDS**

air bubblers

**CLASSIFICATION**

Ice
Suppression

AGRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Ashton, G. D.
"Point Source Bubbler Systems to Suppress Ice"
Cold Regions Science and Technology
Vol 1, pp 93 - 100
1979

**NO.**

AS 79

**SUMMARY**

An analysis of a point source bubbler system used to induce local melting of an ice cover is presented. The analysis uses empirical results of bubbler plume experiments and impingement heat transfer results to determine the rate of melting at the underside of an ice cover. Through a simple energy budget analysis of the ice cover, the melting of the ice cover and resulting extent of open water are determined as a function of air temperatures, depth and air discharge of the source, and water temperature. The analysis leads to a numerical simulation and an example simulation is presented.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

AGRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Ashton, G. D.
"Suppression of River Ice by Thermal Effluents"
CRREL Report 79-30
December 1979

**NO.**

AS 79

**SUMMARY**

The ice suppression resulting from discharge of warm water into rivers during winter is analyzed with emphasis on 2 different cases. In Part I, the case of a thermal effluent fully mixed across the flow section is analyzed to include the effects of unsteadiness in the effluent temperature and the meteorological variations. The location of the ice edge is determined either by a 0°C water temperature criterion or an equilibrium ice melting analysis. The choice of the applicable criterion emerges naturally from the analysis even though the location of the ice edge may be considerably different when a steady-state analysis is done. In Part II, the case of a side discharge of heated effluent is analyzed, also in an unsteady manner, and the effects of transverse dispersion are included in the analysis. Comparisons are made in both Parts I and II to limited field data that are available.

**KEYWORDS**
thermal discharges

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Baines, W. D.<br>"The Principles of Operation of Bubbling Systems"<br>Proceedings of the Symposium on Air Bubbling<br>Ottawa<br>1961 | BA 61 |

**SUMMARY**

The function of the air bubbler is to increase the transport of heat from a body of water to the ice cover or open upper surface. In this paper, the rate at which this heat transport takes place will be discussed. Ideally, the air bubbler should be designed for the minimum rate of heat transport so that the heat in the lake or river will be available for the maximum length of time. This is not feasible because of several gaps in the theory which prevent the complete detailed analysis from being made. Nevertheless, sufficient is known of the heat flow so that the general principles of operation can be delineated. It is thus possible to avoid serious mistakes in the design of air bubblers.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Balanin, V. V.
"Prolongation of Inland Navigation Terms in the USSR"
3rd International Symposium on Ice Problems, IAHR
Hanover, New Hampshire
1975

**NO.**

BA 75

**SUMMARY**

The paper describes in a general fashion, the problems with winter navigation in the USSR.

Three types of navigation channels are discussed

1. the channel packed with broken ice

2. the channel that is regularly cleaned from ice

3. the channel in which ice formation is presented by some means.

The use of icebreakers, bubbler systems and thermal discharges is mentioned.

**KEYWORDS**
icebreakers, air bubblers, thermal discharges

**CLASSIFICATION**
Ice
Suppression
Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bates, C. C.<br>"Navigation of Ice-Covered Waters - Some New Initiatives by the USA"<br>23rd International Navigation Conference, Section II<br>Ottawa<br>1973 | BA 73 |

SUMMARY

The paper presents new initiatives to extend the navigation season on the Great Lakes, St. Lawrence Seaway, Upper Mississippi and its principal tributaries, and on the New England and Alaska coastal regions.

The St. Lawrence Seaway Development Corporation has placed blankets of 3.5 by 60 m closed-cell polyethylene foam planks on the surface of the water and on thin ice along the guide walls of their locks. An appraisal is underway of the effect these planks had on differing widths and depths of water.

To overcome problems of ice bridges forming across channels, the Army Corps of Engineers has undertaken two major projects in the St. Mary's River.

At the Sugar Island ferry crossing, the Corps of Engineers installed an air-bubbler "flush" system at the mainland ferry slip. A continuous current of air kept the water from freezing. Broken ice accumulating in the slip was forced out by a large blast of air.

In the winter of 1970/71, encouraging results were achieved using a bubbler system in Duluth Harbor. It created open areas of water over the pipe about 8 m in width, with reduced ice thickness extending back from the open areas. The harbour ice outside the test area was observed at a maximum of 0.6 m.

The Lime Island site in the St. Mary's River was chosen as the next bubbler system experiment. The thermal gradient was at times as low as 0.6°C from the bottom to the surface. The bubbler extended approximately 910 m, and resulted in thinner ice for an extended navigation season.

(cont'd)

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers, insulation | Ice<br>Suppression<br>Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

**NO.**

BA 73
(cont'd)

**SUMMARY**

The development of offshore oil and natural gas deposits in Anchorage, Alaska, has created a requirement for year-round shipping in Cook Inlet. Ice management problems are created by large ice floes (up to 0.6 m) in fast-moving tidal currents (up to 8 knots). The only solution mentioned is the use of medium-size, shallow-draft icebreakers.

**KEYWORDS**

air bubblers, insulation

**CLASSIFICATION**

Ice
Suppression
Ice Breaking

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

| SOURCE | NO. |
|---|---|
| Bates, H. F. and L. H. Shapiro<br>"Breaking Ice with Gravity Waves"<br>J. Energy Resources Technology<br>Vol 102, pp 148 - 153<br>September 1980 | BA 80 |

**SUMMARY**

The plane-wave impulse response of a laterally compressed floating elastic plate, derived in earlier work, provides a simple means of describing the response of a floating ice sheet to gravity waves induced by a moving vehicle. Vehicle speeds above the cut-off phase velocity produce gravity waves that grow in amplitude with time. These waves grow in amplitude most rapidly when the vehicle speed equals the critical gravity-wave phase velocity. For vehicle speeds above the critical phase velocity, the critical wave is excited at an angle to the vehicle motion; hence, the amplitude grows at a high but decreasing rate as the vehicle speed increases from the critical speed. The critical speed is the optimum speed for breaking an ice sheet by moving vehicle. Vehicles travelling at speeds below the cut-off phase velocity do not excite growing waves that increase the deflection of the ice sheet; thus, vehicular travel below the cut-off speed is recommended. Easily derived plots of the cut-off and critical phase velocities and wave lengths are presented as functions of ice thickness and water depth.

| KEYWORDS | CLASSIFICATION |
|---|---|
| flow developers | Ice Breaking<br>Ice<br>Suppression |

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Bauer, A.
"Explosives for Ice Blasting"
Seminar on Ice Jams in Canada
University of Alberta
May 7, 1973

**NO.**

BA 73

**SUMMARY**

Virtually all areas of Canada are liable to experience hazards resulting from ice packing or flow. The first, and presently the most important problem, is flooding resulting from the formation of ice jams in rivers caused by the breakup of river and lake ice. The second problem is encountered when large drifting ice masses in the oceans run around as they float toward shore or where they bear down on offshore installations such as drilling rigs. This latter problem is in the formative stage but it can be anticipated to become of increasing concern during the next few years.

Many methods to reduce the hazards due to ice breakup have been attempted and one of these entails the use of explosives. The use of explosives for breaking ice has been extensive but has often only met with a varying degree of success which in part has been due to improper charge placement, poor explosives selection, or the failure to recognize significant parameters in the blasing operation.

The best use of explosives is to clear ice from the downstream area of a river, in areas where the channel morphology lends itself to ice jam formation. This is done during the early period of the breakup in order to avoid the potential jamming, and to do it properly a good knowledge of channel morphology is required together with frequent aerial surveys made during breakup.

This paper outlines an approach to using explosives for alleviating problems caused by ice.

**KEYWORDS**

explosives

**CLASSIFICATION**

Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Behlke, C. E. and A. R. McKay
"Artificial Sea Ice Structures for Alaskan Ports"
Proc. Conference on Civil Engineering in
the Oceans
pp 361 - 368
Miami Beach, Florida
1969

**NO.**

BE 69

**SUMMARY**

The authors present a concept of generating artificial sea ice to provide marine structures for Alaskan ports.

A test program carried out in 1969 ran into some difficulties with logistics and ablation during the summer months but the researchers are still hopeful that the method will be feasible and economical for Arctic ports.

More work is necessary in developing methods to reinforce artificial ice island structures and to protect them from warm summer water. At this time, artificial sea ice structures appear to be attractive only in the land-fast ice regions.

**KEYWORDS**

ice control structures, harbour design

**CLASSIFICATION**

Harbour Ice

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bengtsson, L. and J. Sandkvist<br>"Ice Conditions in Lulea Harbor"<br>University of Lulea<br>Sweden<br>1977 | BE 77 |

**SUMMARY**

The authors describe an investigation into ice conditions in Lulea Harbour, Sweden. Accelerated ice growth in these channels varied with the number of ship passages compared with static ice growth. An economic analysis of the increased cost of ice breaking due to accelerated ice growth is presented. The authors conclude there is a strong relationship between the number of vessel passages and the thickness of the ice.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers | Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bock, R. et al<br>"Effects of Ice on Structures"<br>23rd International Navigation Conference, Section II<br>Ottawa<br>1973 | BO 73 |

**SUMMARY**

This paper discusses the effects of ice on structures and on navigation, for inland waterways in Germany.

Traffic is maintained during the winter by icebreaker support. Ferries which cross rivers or canals have particular problems, since tracks kept open by them are continuously filled with loose ice from canal traffic. Grab dredges are often used to remove this ice.

Owing to the small amount of heat storage in the depths of the canals, attempts to keep the ferry bays free of ice by means of propellor-form propulsion equipment or by air bubbler systems have proved fruitless. In Sweden these methods have been more successful owing to the larger quantities of water available.

Problems have occurred in keeping shipping channels open. Traffic can only be maintained if, in the case of 0.12 - 0.15 m ice thickness, no substantial new ice formation occurs. Under freezing conditions, traffic can come to a standstill since the water is constantly mixed by shipping, depleting the small heat reserve available. New ice starts to form immediately, and it cannot be pushed aside, owing to the lack of space in the narrow canals.

The supply of heated cooling water from power stations and industries has been studied. At the time of publication, no major installations have been constructed, but several field tests were conducted.

| KEYWORDS | CLASSIFICATION |
|---|---|
| flow developers, ice forces, air bubblers, thermal discharges | Ice Suppression<br>Ice Removal |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bonisteel, W. D. and A. Bergs<br>"Investigation of a Compressed Air Bubbler System Used For Ice Melting"<br>Proceedings of the Symposium on Air Bubbling<br>Ottawa<br>1961 | BO 61 |

SUMMARY

Rainy Lake is the main obstacle in the path of a highway between Atikokan and Ft. Frances, Ontario. When completed, the Rainy Lake Causeway will carry the highway across the lake providing a direct route for traffic between the two centers.

Two islands in the lake divide the causeway into three separate bridge sections. The two easterly spans support the highway about 5 m above the water and are known together as the low-level section. The westerly spans are elevated to accommodate logging and navigational operations on the lake and are referred to as the high-level section.

To limit the effect of ice pressure on the steel piles supporting the superstructure, a "bubbler" system will be utilized. The first portion of the bubbler system was installed during December 1960. The remainder of the system will follow construction of the high-level section of the causeway.

The purpose of the investigation was to collect information on the deicing system as installed on the low-level section of the Rainy Lake Causeway. The data obtained from the experiments with this system are correlated with those of other installations as recorded in the technical literature. It is expected that this information will be useful for the design of the remainder of the bubbler system on the Causeway. It is also intended to provide design information for bubbler systems in general.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Boulanger, F., E. Dumalo, D. Le Van and L. Racicot
"Ice Control Study - Lake St. Francis,
Beauharnois Canal, Quebec, Canada"
3rd International Symposium on Ice Problems
pp 39 - 48
Hanover, New Hampshire, USA
1975

**NO.**

BO 75

**SUMMARY**

A major concern of winter navigation and power generation is the movement of vessels through the channels which are shared with power authorities and where floating ice booms are used to promote the formation of a stable ice cover, maintain water levels, and ensure regulated flows to the powerhouse.

The main control of ice formation in the Beauharnois Canal is made principally through a series of ice booms set at different strategic locations in conjunction with manipulations of flow. At the outset, these booms are installed from the south bank of the canal to the southern edge of the navigation channel. When the last ship has passed, the booms are extended across the navigation channel to the north shore. Then, when hydrometeorological conditions are favourable, the ice cover formation is on its way. The formation of the ice cover is accelerated by inducing ice floes from Lake St. Francis. Simultaneously, a reduction in flow is necessary for the formation of a stable and smooth ice cover. A complete ice cover in the power canal will preclude further heat transfer thereby eliminating frazil and ice generation, and attendant ice jams. This operation usually takes 1 week.

Some improvements to existing booms have already been introduced and it has been concluded that another boom is required at the entrance to the power canal. The LaSalle Hydraulic Laboratory was commissioned to undertake a hydraulic model study for the proposed boom.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

AGRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bruun, P.<br>"Design Criteria for Nearshore and Offshore Structures Under Arctic Conditions"<br>6th International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Quebec<br>July 27 - 31, 1981 | BR 81 |

SUMMARY

Design of offshore, coastal and harbour structures in the Arctic is reviewed.

A brief discussion of harbours under arctic conditions is provided with special reference to basins with quay-wall or similar installations.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bruun, P. and S. Kjelstrup<br>"The Wave Pump"<br>4th International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Vol 1, pp 288 - 308<br>St. John's, Newfoundland<br>1977 | BR 77 |

SUMMARY

This paper is a continuation of a paper presented at the POAC'73 in Reykjavik, Iceland, dealing with the concept and theory of the wave pump (2).

The wave pump utilizes the momentum of waves at or close to breaking to produce a current. Since 1973, a considerable amount of laboratory experiments have been undertaken and the first prototype is about 200 m long and has a 30 m wide, 50 m long funnel entrance narrowing down to a 10 m, 1.5 m deep channel.

The conclusion is that the wave pump seems to be a useful tool in generation of currents. Its function, the wave action, and its time history depends on shore geometry as well as on the geometry of the trap itself, depth being a most important factor.

One applicaton is for flushing of ice in harbour basins where the sea outside the harbour stays open due to wave agitation while the basin with its calm waters freezes over early.

| KEYWORDS | CLASSIFICATION |
|---|---|
| flow developers | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Bustard, E. E.<br>"Merchant Ships for the Canadian Arctic--Part I"<br>Marine Engineers Review<br>pp 23 - 28<br>November 1973 | BU 73 |

SUMMARY

This paper outlines the requirements for a self-sufficient arctic merchant ship with emphasis on icebreaker design.

The Canadian Government has laid down a policy that icebreaker support will not be provided for normal navigation in the Arctic in the closed season. The cost of this would be prohibitive. The most that can be foreseen at present is emergency services provided in an extreme condition of distress. Any ship engaging in Arctic service in the closed season should, therefore, have the capability of operating unassisted.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers | Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| | |
|---|---|
| SOURCE<br>Calkins, D. J. and M. Mellor<br>"Cost Comparisons for Lock Wall Deicing"<br>IAHR, 3rd International Symposium on Ice Problems<br>Hanover, New Hamshire<br>August 18 - 21, 1975 | NO.<br>CA 75 |

SUMMARY

Lock wall icing conditions on the Great Lakes and St. Lawrence Seaway are described and possible solutions are listed. Cost estimates are included for wall heating by embedded electrical cables and embedded fluid circulation systems, repetitive surface coating with salt solutions, deicing with an inflatable boot, scraping with backhoes, cutting with large chain saws, and slicing with high pressure water jets.

| | |
|---|---|
| KEYWORDS<br>ice cutting, coatings, ice removal | CLASSIFICATION<br>Ice Breaking<br>Ice Suppression |

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Calkins, D. J., D. S. Sodhi and D. S. Deck<br>"Port Huron Ice Control Model Studies"<br>IAHR - International Symposium on Ice<br>Quebec City<br>July 1981 | CA 81 |

**SUMMARY**

The Corps of Engineers, in its study of year-round navigation on the Great Lakes, recognized the problem of ice discharge into the St. Clair River from Lake Huron. Under natural conditions, large quantities of ice often enter the river from the lake, creating ice jams and flooding in the lower reaches of the St. Clair River. The natural ice arch which forms regularly just upstream from the entrance to the river prevents ice transport into the river when it is intact. Whenever a ship goes through such an arch or a storm surge disturbs it, ice discharges into the river. This study deals with the determination of force levels on, and the amount of ice bleeding through the opening in, an ice control structure using natural and synthetic ice floes.

Two studies are presented. A physical model was used to determine the ice discharge through various gap openings in an ice control structure and the hydraulic forces on the structure. The wind stress model evaluated the potential added force due to wind loading on a structure and the ice bleeding through the opening in the ice control structure.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice booms | Ice<br>Diversion |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Cammaert, A. B., D. R. Miller and R. J. Gill
"Concepts for Ice Management at Arctic LNG Terminal"
International Conference on Port and Ocean
Engineering Under Arctic Conditions
1979

**NO.**

CA 79

**SUMMARY**

The paper is concerned with ice management problems anticipated for the Bridport Inlet LNG terminal area (Melville Island), since the natural ice growth averages 2 m. An analysis of the accelerated ice growth caused by repeated ship passages shows that ice thickness can be as much as 6 m at the end of a normal winter.

The paper summarizes a comprehensive review on potential ice management techniques. The technical and economic feasibility of each of the potential solutions are discussed in brief.

From these preliminary investigations, it was concluded that the use of waste heat in the form of a thermal discharge from the liquefaction process is the most effective and reliable way to inhibit ice accumulation near the terminal. The analytical techniques used to predict water temperatures, heat transfer rates to the ice cover, and end-of-season ice growth are discussed.

**KEYWORDS**

thermal discharges

**CLASSIFICATION**

Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Canadian Coast Guard<br>"Ice Navigation in Canadian Waters"<br>Publication of the Canadian Coast Guard<br>MOT, Ottawa<br>1968 | CA 68 |

**SUMMARY**

This publication, written in both French and English, describes in detail the facilities offered by the Canadian Government with regard to navigation through ice in Canada. Communication services from Coast Guard radio stations are outlined and communication information is given for all the regions of Canada affected by ice in the sea. A short section of the publication deals with ship navigation and seamanship as well as giving information necessary for ships requiring and using the services of Coast Guard icebreaking vessels.

In addition, some information is presented on the times of freeze-up and breakup, and ice conditions during the navigation season were applicable for all Canadian waters affected by ice.

Three appendixes are included which give useful reference publications for ice navigation in Canada, an ice reporting code and key for ships navigating in ice, and an abridged ice glossary.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice navigation | Ice<br>Navigation |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Canadian Shipping and Marine Engineering
"Smooth, Tough, Hard-Wearing Hull Coating -
Calculated to Result in Major Savings"
pp 38 - 41
June 1980

**NO.**

CA 80

**SUMMARY**

This article is an update of a report by J. Tarkka of Tecknos Maalit Oy - International Paint's associated company in Finland.

It was found that an old, heavily-corroded ship with a special coating (Inerta 160) which did not wear off during navigation in ice achieved a 30 percent reduction in resistance to ice. Since 1972, over 140 vessels have been coated with Inerta 160 including 20 Canadian vessels.

**KEYWORDS**

coatings

**CLASSIFICATION**

Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

SOURCE

Carey, K. L.
"Performance of the Demonstration Bubbler System
Duluth Harbor, Minnesota"
USA CRREL, Technical Note
1971

NO.

CA 71

SUMMARY

As part of the demonstration bubbler project in Duluth Harbor, CRREL was invited to perform observations and measurements, and to provide a technical assessment of the operation of the bubbler system. The fundamental variable governing the performance of a bubbler system is water temperature. Thus it was decided that water temperature measurements would be obtained before and during the operation of the system, to monitor the extraction of heat from the harbour waters. CRREL also provided recommendations for monitoring the width of the thawed openings by local personnel.

KEYWORDS

air bubblers

CLASSIFICATION

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Carey, K. L.
"Performance of the Demonstration Bubbler System
Lime Island Turn, St. Mary's River, Michigan"
USA CRREL Technical Memorandum
June 1972

**NO.**

CA 72

**SUMMARY**

As part of the Great Lakes and St. Lawrence Seaway Navigation Season Extension - Demonstration Program, CRREL was invited to perform observations and measurements, and to provide a technical assessment of the operation of the bubbler system installed at the Lime Island Turn of the St. Mary's River. The fundamental variable governing the performance of a bubbler system is water temperature. Thus water temperature measurements were obtained during the operation of the system in an effort to monitor the extraction of heat from the river water. CRREL also provided recommendations for monitoring the width of the thawed openings by local personnel.

**KEYWORDS**

air bubblers

**CLASSIFICATION**

Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Carey, K. L.
"Data Report--Saginaw Bay Ice Suppression Test"
CRREL Draft
February 1977

**NO.**

CA 77

**SUMMARY**

CRREL personnel provided assistance in water temperature and ice thickness data collection in a test of the effects of heated effluent on ice suppression.

The expected substantial melt-through of the ice cover did not occur. The anticipated thermal plume either did not develop or was so small and weak that it was not detectable. Evidently, the heat contained in the effluent was rapidly diffused through turbulence and entrainment into the water mass of the bay. Melt-through only occurred directly over the vertical nozzles.

Problems to be overcome in devising a successful system are

-how to avoid or minimize mixing of the heated effluent with the cooler bay water

-how to bring the warmer water to the surface where its heat can be used to melt the ice cover.

**KEYWORDS**

thermal discharges

**CLASSIFICATION**

Ice
Suppression

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Carlson, R. F. and N. R. Morgenstern
"Northern Civil Engineering Research Workshop"
University of Alberta, Edmonton
March 20, 1978

**NO.**

CA 78

**SUMMARY**

The workshop was directed toward six topic areas

- ice and snow engineering
- frozen ground engineering
- hydrotechnical engineering
- environmental engineering
- municipal facilities, design and construction
- resource and transportation facilities, design and construction.

The workshop briefly reviewed state-of-the-art in ice control for navigation and harbours, and identified 14 areas requiring further research.

**KEYWORDS**

ice navigation, ice problems

**CLASSIFICATION**

Ice
Navigation

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

SOURCE

Carstens, T.
"Prevention of Ice Formation by Forced Mixing"
POAC Conference
Norway
1971

NO.

CA 71

SUMMARY

In order to prevent the Rana Fjord, Norway, from freezing due to increased winter inflow of fresh water from hydro power storage reservoirs, an air bubbler was installed at the mouth of the Rana River in 1968.

Three seasons of successful operation have since proven the feasibility of this method of forced mixing under the given set of oceanographical and meteorological conditions.

The mechanics of the mixing process are discussed in the light of observations made partly in experiments prior to construction, and partly in situ after completion of the air bubbler.

KEYWORDS
air bubblers

CLASSIFICATION
Ice
Suppression

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Carstens, T.
"Maintaining an Ice-Free Harbour by Pumping of Warm Water"
POAC Conference
St. John's
1977

**NO.**

CA 77

**SUMMARY**

This paper is concerned with the reduction or elimination of harbour ice by pumping relatively warm water. Brief mention is made of bubbling techniques which work well, but energy wise inefficiently, in fresh water (lakes, rivers) and in layered estuaries with large quantities of heat in the waters beneath a pycnocline.

Bubbling is not generally successful to prevent ice formation in the sea because of the complete overturn and cooling of the water column as sea water cools to the freezing point. Pumping of warmer water then becomes an attractive alternative to bubbling. Modest amounts of waste heat from nearby harbour sources can provide good protection to harbour facilities by maintaining ice-free areas. Unfortunately, the open areas of water can result in ice fog which is undesirable.

Equations with examples are given to calculate heat input requirements to maintain a harbour ice free. Both tidal and lake harbours are considered.

Of important consideration in designing a warm water pumping facility to maintain ice growth suppression in a harbour is that efficient mixing of the warm water with the ambient waters occurs. This is required to prevent partial icing and a warmer "density underflow" out of the harbour.

The paper concludes with several comments concerning some practical aspects of this technique of ice suppression. Initial installation costs may be high if long pipes and insulation are required. Maintenance may be high if the pipe(s) is exposed to wave action. Pipes and jets must not be potential hazards to navigation. The pumping station must supply the energy to effectively produce good mixing of the pumped water with the ambient. It is suggested that 1-10 $w/m^2$ of water surface to be kept open is required. The pumping of warm water does not eliminate the problems of drift ice in or near the mouth of the harbour but can successfully control local ice formation.

**KEYWORDS**

thermal discharges

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Carstens, T.
"Ice in Estuaries and Harbours"
IAHR - Symposium on Ice Problems
Lulea, Sweden
August 1978

**NO.**

CA 78

**SUMMARY**

A survey is presented of ice in estuaries and harbours, primarily viewed as an obstacle to shipping. The possibilities for manipulation are explored, and the present state of predictive modelling is discussed.

Results of model simulations for the somewhat special case of 2-layer fjords with narrow mouths are given. The purpose was to determine the required dilution of freshwater with warm- and salt-fjord water to suppress freezing. These studies were made to avoid adverse ice conditions due to hydropower schemes involving increased winter discharge of fresh water.

Provided warm water is available in sufficient quantities, forced entrainment into the upper layer is feasible by several methods. Forced mixing may work well for the estuary as a whole or locally for harbour basins.

Some special harbour ice problems are mentioned and optimism is expressed regarding their solution.

**KEYWORDS**

thermal discharges, ice problems

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Cook, R. G. and M. D. Wade
"Successful Ice Dusting at Fairbanks, Alaska, 1966"
Journal of the Hydraulics Division
Proceedings of the ASCE
Volume 94, No. HY1
January, 1968

**NO.**

CO 68

**SUMMARY**

The ice and snow cover of the Chena River was dusted with coal dust and fly ash in the spring of 1966 to increase the absorption of solar energy and hasten melting. A near-record snowfall during the winter of 1965/66 caused concern regarding flood damage if an ice jam were to form at the mouth of the Chena River just downstream from Fairbanks. It was hoped that dusting would increase the absorption of the solar radiation to sufficiently weaken and melt the ice to prevent a jam. Theoretically, dusting could increase the radiation absorbed at breakup time in Fairbanks enough to melt an additional 2 cm of ice per day. Measurements of melting rates made in the dusting and clean sections of the river and observations of the river during breakup showed that dusting apparently had a significant beneficial effect. Because of its specific nature and lack of control, this experiment cannot be considered conclusive.

**KEYWORDS**

ice dusting

**CLASSIFICATION**

Ice
Suppression

AGRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

SOURCE

Coveney, D. B.
"Cutting Ice With High Pressure Water Jets"
6th International Conference on Port and Ocean
Engineering Under Arctic Conditions
Quebec
July 27 - 31, 1981

NO.

CO 81

SUMMARY

A high pressure jet of water can be used to cut a slot into or through a sheet of ice, thereby substantially weakening the ice sheet. Such weakening could be particularly useful to enhance the ice-breaking capabilities and/or to reduce the overall power and fuel requirements of an ice-breaking vessel. Although water jet cutting is less efficient in material removal than mechanical modes of cutting, its ability to cut with a substantial mechanical stand-off from the ice sheet and with a concentrated, high level of power input into the ice would provide significant practical advantages for the water jet cutting method.

This paper describes the ice cutting performance of small to moderate scale water jets in freshwater ice and of small scale water jets in a simulated sea ice. The majority of cuts produced a narrow, clean kerf, indicative of erosion in a ductile material, while other cuts produced a wide spalled trench, indicative of spalling in a brittle material. Still others produced a combination of the 2 modes of cutting, with a wide, shallow trench and a narrow, deep kerf below the trench. The causes and the effects of these characteristics on ice cutting performance are discussed, along with the effects of jet traverse speed, nozzle diameter, nozzle pressure, nozzle stand-off, ice characteristics and the overall scale of the system. An empirical relationship, derived by regression analysis, is presented correlating the jet penetration to the power in the jet, the jet traverse speed, the nozzle stand-off and the estimated ice temperature.

KEYWORDS
ice cutting

CLASSIFICATION
Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Danys, J. V.
"Artificial Islands in Lac St. Pierre to Control Ice Movement"
1st Canadian Conference on Marine Geotechnical Engineering
April 25 - 27, 1979

**NO.**

DA 79

**SUMMARY**

During 1959 to 1966, the Department of Transport carried out extensive studies for improving nagivation conditions. Among various proposals to reduce the cost of continuous ice breaking was that of building artificial islands in Lac St. Pierre to control ice movement by retaining ice cover in place. Four artificial islands were built in 1967/68. These, in conjunction with other control works, like ice booms and light piers, have effectively reduced the amount of ice breaking necessary and have helped to improve winter navigation from the St. Lawrence Gulf to Montreal.

**KEYWORDS**

ice control structures

**CLASSIFICATION**

Ice
Diversion

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

De Havilland Aircraft of Canada Ltd.
"Summary Report (1978) Analyses of Air Cushion Ice Breaking Devices Attached to Ships"
DHC Report ECS 78-5
February 1979

**NO.**

DE 79

**SUMMARY**

The overall objective was to develop an air cushion icebreaker device pushed by a ship which would result in optimum performance in breaking and clearing a channel through ice-covered water.

The ice clearing device, in the form of a plow, consisting of 3-tier hydrofoils, was extremely effective at low speed. The induced drag of the device, however, is substantial and suggests that trade-offs between the drag of the ship in an ice channel versus the drag and added design complexity of a plow, together with a ship in a cleared channel, should be studied.

**KEYWORDS**

air cushion vehicles

**CLASSIFICATION**

Ice Breaking

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Dery, J. L.<br>"Design of Wharves for Winter Navigation in the St. Lawrence River"<br>Conference on Port and Ocean Engineering Under Arctic Conditions<br>Vol I<br>1981 | DE 81 |

## SUMMARY

Although there are records of winter navigation on the St. Lawrence River dating back for many years, navigation in ice-bound waters throughout the winter season from Montreal to the ocean has been on a regular schedule only for the last 20 years.

In this paper, ice and climate conditions prevailing in the St. Lawrence valley during the winter season are documented, and a short history is given of wharf design in the area and ice problems encountered.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

**SOURCE**

Dick, T. M.
"Description of Air Bubbling Systems at Cambridge Bay and Tuktoyaktuk NWT"
Proceedings of the Symposium on Air Bubbling
Ottawa
1961

**NO.**

DI 61

**SUMMARY**

Owing to their remote location, wharves in Arctic waters are costly to repair when damaged by ice. To combat this, the Harbours and Rivers Branch (Department of Public Works) has installed pneumatic deicing systems at Tuktoyaktuk, at the mouth of the MacKenzie River, and at Cambridge Bay on the southern shore of Victoria Island. It is hoped that the air bubbles will prevent thick ice freezing to the piles and lifting them as the tide rises. Open water is not necessary to prevent uplift. It is sufficient to reduce the thickness of the ice so that it will fail before the pile is lifted.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Dick, T. M.
"Limits to Navigation by Ice in Port of Churchill"
Journal of the Waterways and Harbors Division
Proc. of the ASCE, Volume 93, No. WW4
November 1967

**NO.**

DI 67

**SUMMARY**

Churchill Harbor lies on the western shore of Hudson Bay at the mouth of the Churchill River. Ice conditions in the harbor limit the navigation to the period from July to October. Icing conditions in Hudson Bay, Hudson Strait, and Churchill Harbor are discussed.

Ice concentration at the shipping berth and dock is aggravated by the action of surface currents which force the pancake and frazil ice against the dock face during the ebb tide, forming a band approximately 0.3 - 0.5 km across. It has been calculated that the harbour becomes unnavigable about 22 days in advance of the average final freeze-up.

The only ice management technique investigated was the diversion of flow for the river, which would inhibit frazil ice production, and reduce the volume of ice.

**KEYWORDS**
ice navigation

**CLASSIFICATION**
Ice
Diversion

**SOURCE**

Donnelly, P.
"An Outline of the Design and Operation of the Montreal Ice Control Structure"
Department of Public Works
Ottawa
(no date)

**NO.**

DO

**SUMMARY**

Land reclamation in Montreal Harbour to develop a site for the Canadian Universal and International Exposition (EXPO'67) involved narrowing of the St. Lawrence River channels. This narrowing of the river channels increased the dangers of ice jams and, consequently, the flood hazard not only to the EXPO'67 site itself but also to the City of Montreal and adjacent municipalities.

To minimize the danger of winter floods caused by ice jams, a special ice control structure was built across the river at the lower end of LaPrairie Basin about 5 km upstream from the EXPO'67 site. This structure, which is almost 2,100 m long, consists of 72 reinforced concrete piers, between fitted removable, floating steel stop logs.

This paper reviews the ice problem in the Montreal area of the St. Lawrence, summarizes the results of the hydraulic model studies which were carried out to test the effectiveness of the proposed ice control structure, describes briefly the design of the structure, and closes with a note on the limited operating experience gained during the first season of operation.

**KEYWORDS**

ice control structures

**CLASSIFICATION**

Ice
Diversion

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Dotson, W. A.<br>"Operational Details of Project Polynya"<br>Proceedings of the Symposium on Air Bubbling<br>Ottawa<br>1961 | DO 61 |

SUMMARY

A study was undertaken to determine the feasibility of extending the shipping season at Thule, Greenland. Using information obtained from published accounts of successful air-bubble deicing and ice prevention techniques utilized in Scandinavian countries, United States and Canada, it was decided to attempt the installation of a deicing system at Thule, Greenland.

As a result of experience in air-bubble deicing and ice prevention in both Sweden and Canada, Atlas Copco Eastern Inc., of Toronto, Ontario, was contacted for advice and technical assistance. Several other possible suppliers of desired equipment were contacted but the necessity of immediate delivery of equipment proved to be a problem. Further, owing to lack of experience, no agency could furnish the technical assistance required. Atlas Copco Eastern, Inc., at Paramus, New Jersey, contracted to furnish all technical and material assistance for initial installation.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

AGRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Evans, J. T.<br>Pneumatic and Similar Breakwaters<br>Proc. Royal Society London<br>Ser. A, Volume 231, pp 457 - 466<br>1955 | EV 55 |

**SUMMARY**

The investigation described in this paper shows that the surface currents set up by air injection, and the distribution of the water velocity within the currents, can be matched by currents set up by water jets, and that the two currents so matched have almost the same wavedamping effect whether they are set up by water jets or by air. It is concluded that the bubbles as such have at most a very small effect on the wave motion.

It is found that waves of small amplitude are stopped in the way predicted theoretically, but that as the amplitude increases, the surface current necessary to stop waves of a given length increases.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers, flow developers | Ice<br>Suppression |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Fenco Ltd.
"Ice Control Experiment - Canadian Arctic"
Bulletin of the Permanent International Association of Navigation Congresses, 1967
No. 23/24
1967

**NO.**

FE 67

**SUMMARY**

In 1965, the Richfield Oil Corporation was carrying out geological surveys in Hudson Bay. It was determined that if the main drill boat could be wintered in the Port of Churchill, an additional month could be gained each season for onsite work. An experimental program was developed to determine whether a safe winter berth could be assured for the vessel.

Bubbler systems for Thule, Greenland; the Antarctic; Tuktoyaktuk, NWT; and Cambridge Bay, NWT are referenced.

At the proposed winter berth the average thickness of ice varies from 1.3 - 2.0 m. A water salinity gradient is always present. No significant thermal reservoir exists however. The test consisted of utilizing a submersible electric pump as the prime mover of underlying water layers.

The results of the experiment are not very conclusive, although the authors claim that a limited ice-free area can be maintained by cutting an opening and maintaining surface turbulence.

**KEYWORDS**
air bubblers, flow developers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Fonstad, G. D.<br>"The Explosive Demolition of Floating Ice Sheets"<br>6th International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Quebec<br>July 27 - 31, 1981 | FO 81 |

SUMMARY

Demolition of floating ice sheets is a common technique used to clear shipping lanes, construct temporary port facilities in Arctic and Antarctic environments and to mitigate ice jam effects on inland waterways both before and after ice jam formation. Mellor carried out a review and analysis on the data existing to 1972 of the effects of point charges on floating ice sheets. On the basis of this analysis, Mellor made preliminary recommendations of the optimum charge size and placement depth as a function of ice thickness.

In this paper, a series of tests conducted to confirm Mellor's analysis and to determine the optimum spacing of charges in a row, are described. The appropriate dimensionless terms are derived, and equations giving the optimum ice sheet demolition parameters are given.

| KEYWORDS | CLASSIFICATION |
|---|---|
| explosives | Ice Breaking |

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Frankenstein, G. E. and N. Smith
"The Use of Explosives in Removing Ice Jams"
IAHR Symposium - Ice and Its Action
on Hydraulic Structures
Reykjavik, Iceland
1970

**NO.**

FR 70

**SUMMARY**

A brief history of the use of explosives for ice jam removal is discussed. Ammonium nitrate mixed with fuel oil is considered the best explosive because of its cost and safety features. For maximum effect the charge should be placed in the water below the ice. A curve is included which gives maximum crater hole diameter as a function of the cube root of the charge weight.

**KEYWORDS**

explosives

**CLASSIFICATION**

Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Frederking, R. and N. K. Sinha<br>"Ice Action on Wharf at Strathcona Sound"<br>4th International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Newfoundland<br>September, 1977 | FR 77 |

SUMMARY

A program to determine ice forces and behaviour was carried out on a wharf at Strathcona Sound on Baffin Island during the winter 1975/76. Observations at the site revealed that tidal action resulted in the formation of an increasingly wide and thick zone of ice between the wharf and the natural ice cover. A qualitative model for developing ice pressures is postulated based on this behaviour. The transducers selected to measure horizontal ice pressures proved to be unsatisfactory so no direct measurements were obtained. It was possible however, from secondary calculations, to establish that horizontal ice pressures of the order of 500 kPa were developed.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice forces | Harbour Ice |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Frederking, R.M.W.<br>"Ice Action on Nanisivik Wharf, Strathcona Sound, NWT, Winter 1978 - 1979"<br>Canadian Journal Civil Engineering<br>Vol 7, pp 558 - 563<br>1980 | FR 80 |

**SUMMARY**

Field observations have been made over 3 winters at a vertically-faced wharf in an area of limited horizontal ice movement but substantial vertical movement due to tides. Ice thickness was profiled and vertical ice movements were measured. A reasonably consistent pattern of ice behaviour adjacent to the wharf was established, characterized by the formation of a transition ice zone between the first-year sea ice and the wharf. The behaviour and factors affecting growth of this zone are described.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice forces | Harbour Ice |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Fuglum, A.<br>"Experiences from Engineering Works in the Port of Drammen"<br>1st International Conference, Port and Ocean Engineering Under Arctic Conditions<br>Norway<br>1971 | FU 71 |

SUMMARY

The Port of Drammen is situated approximately 40 km from Oslo, Norway at the bottom end of The Drammensfjord. Every year for about 3 - 4 mo, the fjord is frozen in for about 19 km into the heart of the port. Ice thickness normally reaches 1.0 - 1.3 m. The entrance to the port is maintained by icebreakers, establishing "precut" lanes.

The use of a bubbler system for clearing ice from the waterfront is briefly mentioned.

A study is underway to reduce costly maintenance programs for snow and ice clearance. Some innovative solutions like total enclosure of the port area, or moving the port into a large heated hall in the mountainside, are being investigated. Thermal discharge and ice dusting are also being studied.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers, port enclosures, thermal discharges, ice dusting | Ice Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Gaither, W. S. and R. E. Dalton
"All-Weather Tanker Terminal for Cook Inlet, Alaska"
Proc. of the ASCE, Journal of the Waterways and
Harbors Division, WW2
May 1969

**NO.**

GA 69

**SUMMARY**

Cook Inlet extends approximately 240 km northeast from the Gulf of Alaska to Anchorage, and varies in width from 16 - 80 km.

The environmental conditions do not encourage year-round shipping. The inlet does not freeze into a continuous ice sheet, but large ice floes travel with the tides.

The basic requirement of the offshore tanker berth was that it could expand to accommodate 100 000 dwt tankers on a year-round basis. The short construction season and high costs of on-site fabrication led to the selection of large prefabricated units. The basic configuration for the loading platform is that of a barge supported by 4 permanent caisson legs. The breasting dolphins consist of 4 vertical steel legs joined below the ice level by pipe bracing.

No ice management techniques were mentioned in the paper.

**KEYWORDS**

harbour design

**CLASSIFICATION**

Harbour Ice

AGRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Garfield, D. E., B. Hanamoto and M. Mellor
"Development of Large Ice Saws"
CRREL Report 76-47
Hanover, New Hampshire
1976

**NO.**

GA 76

**SUMMARY**

This report describes two mechanical ice-cutting systems for the removal of ice collars at the high pool level on the Poe Lock of the St. Mary's Falls Canal at Sault Ste. Marie, Michigan. One system was a narrow kerf (8.3 cm wide) coal-cutting chain saw mounted on a bar, driven by a 65-hp wheeled trencher. The other system was a lumber-cutting chain saw mounted on a bar, driven by a 30-hp wheeled soil trencher which cut a 1.4-cm wide kerf. The lumber-cutting saw's bar was too flexible and the desired cutting traverse speed was not met. The coal-cutting saw cut 2-m deep ice collars at traverse speeds of up to 3.3 m/min and is acceptable. With a few modifications, the coal-cutting saw would be operational.

**KEYWORDS**
ice cutting

**CLASSIFICATION**
Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Gilpin, R. R.<br>"The Ablation of Ice by a Water Jet"<br>Canadian Society for Mechanical Engineering Transactions<br>Vol 2, No. 2<br>1973/74 | GI 73 |

SUMMARY

When a jet of warm water is directed perpendicular to the surface of a solid block of ice, a roughly cylindrical cavity is ablated in the ice. After an initial transient period, the cavity develops an essentially constant shape which penetrates at a uniform rate into the ice. The rate of penetration of the ice is linearly dependent on the temperature of the water in the jet which indicates that a convective heat transfer process controlled the ablation rates. The rate can, therefore, be expressed in terms of effective heat transfer coefficients and these can be correlated using the normal convective heat transfer correlation parameters of Nusselt's number and Reynold's number. These parameters produce good correlation of ablation rates for all jet velocities, water temperatures and nozzle diameters used.

| KEYWORDS | CLASSIFICATION |
|---|---|
| thermal discharges | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Girgrah, M. and V. K. Shah<br>"Construction of a Deep-Sea Dock in the Arctic"<br>Proc. of the Fourth International POAC Conference<br>St. John's, Newfoundland<br>September 1977 | GI 77 |

**SUMMARY**

The authors describe design requirements and methods selected to construct a deep-sea dock at Strathcona Sound, Baffin Island (lat 73°N, long 84.5°W) to serve as a shipping terminal for the lead/ zinc mines at Nanisivik. The berth was designed to service vessels up to 50 000 dwt and to have a berthing length of some 365 m.

The paper deals mainly with the methods employed during construction, the problems encountered, and the solutions devised.

The authors conclude that using the ice as a working platform provided an unlimited working area which considerably simplified construction work methods and procedures. The severe climate, in this instance, presented no problems. In fact, it provided a natural aid to an economical form of construction which permitted the saving of almost $1,000,000 on the estimated construction cost.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

| | |
|---|---|
| **SOURCE**<br>Goode, J. W. and A. E. Teller<br>"Ice Breakage with Explosives"<br>1st International Conference, Port and Ocean Engineering Under Arctic Conditions<br>Norway<br>1971 | **NO.**<br>GO 71 |

**SUMMARY**

Experimentation has shown that ice thickness is the most important consideration. Beyond 2 m, an explosive with high gas-producing properties is required. Displacement of the ice in total must occur over a large area and all at the same time. The charge should be lowered into the water beneath the ice at some optimum depth, which is twice the thickness of the ice. Sleeper charges could be placed during open water months, with detonation reserved until necessary.

| | |
|---|---|
| **KEYWORDS**<br>explosives | **CLASSIFICATION**<br>Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Griesbach, R. J. and H. Kremer<br>"Conceptual Study of Marine Terminal Facilities in the Arctic"<br>23rd International Naval Congress<br>Permanent International Association of Navigation Congresses<br>Ottawa<br>1973 | GR 73 |

SUMMARY

This paper deals primarily with the broad range of structural considerations inherent in the design of an offshore arctic marine terminal and outlines some of the problems relevant to design, layout and operation of the facilities, including oil pipelines. Design aspects and structural design criteria are outlined. Design alternatives are discussed and conclusions reached as to the most practical and economical means of constructing such facilities within the terms of reference of the study.

For conceptual study purposes, facilities were assumed to be located in the Herschel Island area.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Grove, C. S. Jr., S. T. Grove and A. R. Adium
"The Theory and Use of Aqueous Foams for Protection of Ice Surfaces"
In Ice and Snow--Properties, Processes and Applications
MIT Press
Cambridge, Massachusetts
1963

**NO.**

GR 63

**SUMMARY**

This paper describes laboratory tests carried out on an aqueous foam with a view to determining the feasibility of its use on runways to prevent thawing during warm periods.

Experiments were carried out on methods of foam generation, the effect of stabilizers on the deterioration rate of the foam and the insulating properties of the foam. It was generally concluded that the foam would decrease the ice melt rate considerably but that stabilizing agents are necessary to provide long-term protection.

**KEYWORDS**

insulation

**CLASSIFICATION**

Ice Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Haggkvist, K.<br>"Combination of a Sinking Warm Water Discharge and Air Bubble Curtains for Ice Reducing Purposes<br>6th International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Quebec<br>July 27 - 31, 1981 | HA 81 |

SUMMARY

The work described in this report indicates that a considerable ice reduction effect in a limited area can be obtained by combining a sinking warm water discharge and a bottom-located air bubble discharge. A laboratory experiment and a theoretical analysis are presented. In an example based on the conditions in Lulea Harbour in northern Sweden, it is shown that over an area of 50 by 500 m, the ice thickness can be reduced to less than 0.2 m, which is less than 25 percent of the maximum natural ice thickness.

| KEYWORDS | CLASSIFICATION |
|---|---|
| thermal discharges, air bubblers | Ice<br>Suppression |

| SOURCE | NO. |
|---|---|
| Hall, T. N.<br>"Economic and Social Aspects of Icebreaking on the St. Lawrence Seaway"<br>10th Conference Symposium on Air Cushion Technology<br>Calgary, Alberta<br>October 27, 1976 | HA 76 |

SUMMARY

This paper reviews the economic and social consequences of having St. Lawrence Seaway facilities idle for approximately one-third of the year. Plans for extending the season are outlined and discussion centers around possible development of ACV's for use in the Great Lakes as a more economic alternative to conventional icebreakers.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers | Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Harbour and Shipping<br>"Innovative Icebreaker CCGS Pierre Radisson"<br>pp 25 - 30<br>August 1978 | HA 78 |

SUMMARY

The primary purpose of the Canadian Arctic class icebreaker is

-escorting ships through ice-covered waters

-clearing navigational channels of ice

-flood control duties in the St. Lawrence

-breaking out ice-covered berthing areas in the principal harbours of the Great Lakes and both the St. Lawrence Gulf and the River.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers | Ice Breaking |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Haynes, F. D.<br>"Survey of Design Criteria for Harbors and Channels in Cold Regions"<br>CRREL Report 76-3<br>March 1976 | HA 76 |

SUMMARY

This report is an annotated bibliography on harbour and channel design in cold regions. Emphasis is on the effects of ice forces on structures but there are also references on ice suppression.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Haynes, F. D., G. D. Ashton and P. R. Johnson
"Performance of a Point Source Bubbler Under
Thick Ice"
IAHR - International Symposium on Ice
Quebec City
July 1981

**NO.**

HA 81

**SUMMARY**

Air bubbler systems are used to suppress ice formation and prevent ice damage to structures. Injection of air into the slightly more dense, warm water at the bottom of a body of freshwater raises the warm water to the surface. A bubbler system provides a simple and inexpensive means of suppressing ice if the body of water has the necessary thermal reserve. A study was conducted with a point source bubbler to examine its performance when intalled under an existing layer of thick lake ice.

When a small hole existed in the ice above the bubbler, the induced flow caused rapid melting of the sides of the hole at and below the water level. Melting progressed outward until the ice cavity reached a radius of 3 m, at which time the unsupported ice sheet above the cavity collapsed. The outer edge of this thin ice plate remained in place but the center sagged into the water and melted.

When the bubbler was placed under a solid ice sheet without an escape hole, the air escaped laterally under the ice toward the shore. After one day, the air began to escape through the ice directly above the bubbler. A cavity was formed to the hydrostatic water level and then enlarged as with the earlier test. Again, the unsupported ice above the free water level failed, sagged into the water, and melted.

The radial flow at the surface melted the ice sheet on the periphery of the cavity. After the ice above the cavity collapsed, melting continued at the periphery of the open water. The melting front of the cavity was approximately vertical with minor irregularities in the side wall. Little evidence was found of thinning of the ice sheet beyond the edge of the open pond.

The mixing of the water by the bubbler disturbed the stratified thermal regime in the vicinity of the bubbler. Velocity and temperature profiles are given for the bubbler plume and radial flow pattern. A heat transfer analysis is also included.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Hearnshaw. J. D.
"The ACV Icebreaking Bow Development Program--An
Overview and Status Report"
Transport Canada R&D Centre
Montreal, Quebec
March 1977

**NO.**

HE 77

**SUMMARY**

This paper describes Phase I of Transport Canada's ACV Icebreaking Bow Development Program. An ACT-100 air cushion vehicle was converted to an ice-breaking platform suitable for attachment to the bow of the Coast Guard icebreaker Alexander Henry. Full-scale field trials were carried out at Thunder Bay.

The Phase I trials were successful to the point that the Canadian Coast Guard has undertaken design development of a prototype air-cushion platform ice-breaking attachment for future deployment in the ice-breaking fleet.

**KEYWORDS**

air cushion vehicles, icebreakers

**CLASSIFICATION**

Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Hill, I. K., A. B. Cammaert and D. R. Miller
"A Laboratory Study of Heat Transfer to an Ice Cover from a Warm Water Discharge"
6th International Conference on Port and Ocean Engineering Under Arctic Conditions
Quebec
July 27 - 31, 1981

**NO.**

HI 81

**SUMMARY**

A warm water discharge has been proposed to limit ice buildup around an Arctic liquid natural gas terminal. One approach consists of high velocity jet diffusers inside a floating curtain surrounding the terminal area, resulting in the suppression of ice growth.

Water temperatures and velocities were predicted from a thermal plume model. Calculation of the effect of the flow on ice thickness requires knowledge of the rate of heat transfer between the water and ice. Experimental flume observations were made to confirm the relationship used for the heat transfer analyses.

This paper describes the experimental program conducted in an ice flume at the Acres' laboratories. The heat transfer rate was obtained by measuring the temperature profile through the ice cover and the change in ice thickness with time.

Tests were conducted with both freshwater and saline ice. The parameters of ice thickness, water depth, water velocity and water temperature were varied. The test data are presented and compared with the analytical results.

**KEYWORDS**
thermal discharges

**CLASSIFICATION**
Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Hill, J. E.
"Air Bubbler Ice Control Experiment in
Thunder Bay"
Lakehead Harbour Commission for Transport Canada
May 1980

**NO.**

HI 80

**SUMMARY**

This report presents the results of an experiment with the use of air bubblers to control ice formation in grain elevator slips. Ships entering the slips at the end of the shipping season pile up ice in the slip, and the time required for this added accumulation to melt can delay the use of the slip in spring, or at the very least, make it difficult to predict when the slips will be accessible.

The primary objective of this experiment was to evaluate the use of air bubblers to control ice formation in the slip and, more specifically, to determine the capital and operating cost of such a system and the necessary air volumes and pressures required to control ice formation.

The system installed was found to be effective in controlling ice formation. The total costs per season excluding the installation capital cost of a 1,200-m system were found to be approximately $5,400. Minimum air pressure requirements were found to be 3.5 kg/cm$^2$ at a minimum volume of 9.2 m$^3$/min.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Hope, A. A., J. Udell and M. Tapiero et al
"Air Cushion Icebreaking Bow Development
Program, 1975 - 1978"
Transport Canada
Montreal
1980

**NO.**

HO 80

**SUMMARY**

This report summarizes the activities undertaken in a 4-year program to develop an air cushion platform as an ice-breaking device attached to a ship's bow (i.e., low speed ice-breaking method).

The conventional approach to improve ice-breaking capability is to increase the power and weight of the ship and to improve the hull shape. The objective of this program was to improve the capability by attaching an air cushion platform (ice-breaking bow) to the ship. The development program includes mathematical analysis, scale modelling, economic analysis and 2 winters of full-scale testing in Thunder Bay, Ontario. Results showed that

-attaching an air cushion ice-breaking platform to the bow of a ship in intact uniform ice cover appreciably enhances the ship's ability to penetrate the ice cover

-this method of breaking a given area of ice achieves considerable savings.

Further development is required to optimize the design of air cushion icebreakers in terms of size and application. Mathematical models were devised, but validation by experimental data was not achieved. Such predictions are the most cost-effective means on which to base future designs of air cushion icebreakers for operation in Canada, including the Arctic.

**KEYWORDS**
air cushion vehicles

**CLASSIFICATION**
Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Hulgaard, E. and T. Sorensen
"Ice Cover Prevention by Means of Air Bubbles, Narssaq, Greenland"
1st International Conference, Port and Ocean Engineering Under Arctic Conditions
Norway
1971

**NO.**

HU 71

**SUMMARY**

Narssaq is a small village in the southern-most part of Greenland, located at the middle of one of the long narrow fjords in this region. Harbour facilities are planned in Colony Bay, where the water depth is 5 - 10 m and the tidal range about 2 m. The ice in this area is usually landfast, although it is occasionally carried away by offshore gales.

Field measurements indicated a maximum ice thickness of 0.15 m. A salinity gradient was present due to the inflow of freshwater at the head of the bay.

An experimental air bubbler system was set up in 1967, which suggested that a very significant improvement in ice conditions at Narssaq could be achieved by a properly designed system.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Hung, S. C.
"Ice Information and Ice Control Programs of the Saint Lawrence Seaway Development Corporation"
Glaciological Dat.
GD-9
December 1980

**NO.**

HU 80

**SUMMARY**

Ice Information Program

Major activities are

-vertical aerial photography of ice cover
-time lapse photography of ice formation and movement
-remote sensing of ice thickness and hanging dams
-water temperature measurements
-weather data monitoring.

Ice Control Program

The objective of this activity is to identify and demonstrate alternative methods for permitting navigation into and through the winter season. Four major projects completed under this program are

-Installation and Testing of the Ogdensburg - Prescott Ice Boom Gate in 1974

-Copeland Ice Boom Testing (1974/75)

-Copeland Cut Hydraulic/Ice Model Study (1976)

-St. Lawrence River Ice Boom Modification Study (1977 to 1980).

**KEYWORDS**

ice navigation, ice booms

**CLASSIFICATION**

Ice
Diversion

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Ince, S.
"Winter Regime of a Tidal Inlet in the Arctic and the Use of Air Bubbler for the Protection of Dock Structures"
National Research Council
Ottawa
1963

**NO.**

IN 63

**SUMMARY**

Shipping the Canadian Arctic is limited to about 2-1/2 mo in summer. During this short period all communities have to be supplied with sufficient provisions and fuel to last the long winters. The Department of Public Works of Canada has built wharves and docking facilities in various Arctic centers to speed up the unloading operations. Many of the conventional pile structures have been destroyed by the 2-m thick ice layer, which grips the piles and moves them up and down in response to the tide. To prevent this, an air bubbler system was installed 3 years ago at Tuktoyaktuk, NWT to inhibit the formation of ice around the wharf. This unit has been operating successfully since that time and no further damage has been reported. This first success inspired the installation of a second unit at Cambridge Bay, NWT where similar difficulties were being encountered. The air bubbler system at Cambridge Bay did not fulfill its promise and the wharf was damaged. This had been predicted, but the success at Tuktoyaktuk, despite the suspected influence of the MacKenzie River, was a mystery. In April 1961 the author investigated the bubbler system and its oceanographic environment at Cambridge Bay, and in April 1962 those in Tuktoyaktuk.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Ince, S.
"A Guide to the Design of Air Bubblers for Melting Ice"
The Ice Seminar
CIM Special, Volume 10
1968

**NO.**

IN 68

**SUMMARY**

This paper outlines a design procedure for estimating the air and power requirements of air bubbler systems and develops a heat transfer analysis for the case of a bubbler used to melt an ice sheet.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Instanes, B.<br>"Coal-Loading Pier in Svea, Svalbard (Norway)"<br>International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Trondheim<br>1979 | IN 79 |

**SUMMARY**

A description is provided for a cellular sheet-pile pier for coal-loading at Kapp Amsterdam, Norway. Design criteria for ice forces acting on the pier are also given.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design, ice forces | Harbour Ice |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Jasinska, E. and W. Robakiewicz<br>"Methods of Preventing Ice Propagation in Confined Waters"<br>23rd International Navigation Conference, Section II<br>Ottawa<br>1973 | JA 73 |

**SUMMARY**

Experience is reported on the use of air bubbling systems in Poland. Details are given concerning installations used successfully to keep ice out of ferry berths, and an experiment to investigate keeping ice out of harbour areas.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Juurmaa, K.
"The Wartsila Air Bubbling System"
Polar Record
Vol 19 (119), pp 121 - 127
1978

**NO.**

JU 78

**SUMMARY**

A method to reduce friction between an icebreaker's hull and ice is presented. A mixed flow of air bubbles and water is produced, arising from compressed air being forced through a series of nozzles at specified intervals near the bottom of the ship. When the air rises along the hull in the form of bubbles, it creates a strong current of water and air which forms a layer between the hull and the ice. This has the result of reducing ice resistance.

The test results indicate that the ice thickness limit for an icebreaker can be increased by using the air bubbling system.

**KEYWORDS**

icebreakers, air bubblers

**CLASSIFICATION**

Ice Breaking
Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Keribar, R., R. S. Tankin and G. D. Ashton
"Computer Simulation of Bubbler-Induced Melting of Ice Covers Using Experimental Heat Transfer Results"
Canadian Journal Civil Engineering
Vol 5, pp 362 - 366
1978

**NO.**

KE 78

**SUMMARY**

After a brief description of the physical phenomenon associated with artificial suppression of winter ice sheets over water bodies by "bubbler systems" or submerged air injectors, results of laboratory experiments conducted to determine bubbler-induced heat transfer coefficients are reported. Implications and validity of results are discussed.

As a second step, a procedure for computer-simulating the behavior of an ice sheet whose thickness is controlled by a bubbler system operating intermittently over a long period of time is developed. The simulation uses experimentally determined bubbler heat transfer coefficients, weather data, site characteristics, and desired performance as input data, and a finite difference method to solve the equations governing the ice thickness and temperature profile. Through an example simulation, the usefulness of the procedure in predicting ice thickness and temperature profile histories, and the effectiveness or suitability of a given bubbler system are demonstrated.

**KEYWORDS**
air bubblers

**CLASSIFICATION**
Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Kerr, A. D.<br>"Forces an Ice Cover Exerts on Rows or Clusters of Piles Due to a Change of the Water Level"<br>International Association of Hydraulic Research<br>Lulea, Sweden<br>August 7 - 9, 1978 | KE 78 |

SUMMARY

A pier of a marina or of a related structure often consists of rows or clusters of slender piles driven into the submerged soil, and of a platform which is placed over them. During the cold winter days, an ice cover forms over the water which is often solidly frozen to the piles. Subsequently, any change of the water level causes the ice cover to exert forces on the piles. In the present paper, analyses are presented for the determination of the vertical forces a floating ice plate exerts on a variety of pile configurations. To simplify the use of these analyses, the results were evaluated numerically for a variety of parameters and are presented as graphs.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice forces | Harbour Ice |

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Kivisild, H. R.
"Year-Round Oil Terminal in Ice Covered Waters"
1st International Conference, Port and Ocean
Engineering Under Arctic Conditions
Norway
1971

**NO.**

KI 71

**SUMMARY**

A marine terminal has been designed to receive crude oil tankers up to 100 000 dwt, and product tankers up to 20 000 dwt, at a location on the south shore of the St. Lawrence River near St. David de Levis, Quebec.

The wharf is designed for severe ice action and is designed to operate on a year-round basis. Icebreaker cells have been placed upstream from the berth to provide protection from very large ice floes.

**KEYWORDS**

harbour design

**CLASSIFICATION**

Harbour Ice

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Knight, G. R. and A. C. Condo
"Design and Evaluation of Insulated and
Uninsulated Roadway Embankments for the Arctic"
Proc. Symposium on Cold Regions Engineering
pp 195 - 226
University of Alaska
March 1971

**NO.**

KN 71

**SUMMARY**

This paper presents design criteria for using polyurethane as an insulating material along Arctic roadway embankments to prevent permafrost melting.

A "Prudhoe Test Road" was constructed to verify theoretical calculations and results were very encouraging.

**KEYWORDS**

insulation

**CLASSIFICATION**

Ice
Suppression

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Koren'kov, V. A., G. A. Morozov, A. F. Nikolaev
and A. I. Shkoda
"Experience With Use of Ice-Cutting Machines
for Preventing Ice-Jam Formation"
Gidro-teknicheskoe Stroitel'stro
No. 2, pp 42 - 45
1975

**NO.**

KO 75

**SUMMARY**

The search for more reliable and economical means for preventing ice-jam formation led to development of a self-propelled ice-cutting machine with the following specifications.

| | |
|---|---|
| -engine capacity | 115 hp |
| -ice-cutting parameters | |
| -depth | to 1.5 m |
| -width of cut | 0.15 m |
| -cutting speed | to 350 m/h |
| -travel speed | to 18 km/h |
| -machine weight | 4 tonnes |

The use of a rotary-helical drive on the ice-cutting machine permits cutting of ice covers up to 2 m thick. Tests over 3 years on rivers and reservoirs proved successful in preventing ice-jam formation. Photographs and schematic diagrams of the ice-cutting operation are included in the journal article.

**KEYWORDS**

ice cutting

**CLASSIFICATION**

Ice Breaking

|  |  |
|---|---|
| **SOURCE**<br>Korzhavin, K. N., et al<br>"Influences of Ice Upon Construction and Methods of Combatting Ice Problems"<br>CRREL Report<br>Draft Translation 422<br>December 1974 | **NO.**<br>KO 74 |

**SUMMARY**

This collection of articles deals with the variety of ice related factors which influence the specifications for building in an Arctic environment. Based on the studies done concerning the effect of ice on completed structures, these articles present logical approaches to estimating effective ice loads and how to determine the necessary ice protective measures while building reservoirs, hydraulic structures, harbour ships, etc. Several articles concern the weakening of ice strength or increasing the rate of thawing.

|  |  |
|---|---|
| **KEYWORDS**<br>harbour design, ice problems | **CLASSIFICATION**<br>Harbour Ice |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Laframboise, J. E.
"Comparative Analysis of Ice-Breaking:
Conventional Versus Air-Cushion"
13th Canadian Symposium on Air Cushion
Technology
Montreal, Quebec
September 17 - 19, 1979

**NO.**

LA 79

**SUMMARY**

The operating principles of both conventional and air-cushion icebreakers are reviewed. Similarities and differences for the two types of ice-breaking technology are outlined and anticipated developments in the short and long terms are presented.

The comparative analysis suggests that two concepts should be pursued.

-Shallow bow angles and low friction produce better icebreakers.
-Dynamic ice breaking where ice is disrupted through wave energy.

Potential is also seen for notching an ice plate with cutters or high velocity water jets to reduce impact strength and, therefore, its rupture load and induced drag on the ship.

**KEYWORDS**

air cushion vehicles, icebreakers

**CLASSIFICATION**

Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Laframboise, J. E.
"The Transportation Development Centre
Contribution to Air Cushion Technology"
15th Canadian Symposium on Air Cushion
Technology
pp 188 - 207
Toronto, Ontario
September 29 - 30, 1981

**NO.**

LA 81

**SUMMARY**

This paper reviews the research carried out by the Transportation Development Centre in air cushion technology since 1970.

Current activities in air cushion technology are directed toward ice breaking, arctic operations and overland transportation. In addition to continuing ice-breaking trials with the Hoverlift System Ltd. ACIB at Thunder Bay, research is being carried out in an attempt to integrate fluid cushion devices in the redesigned bow of an icebreaker. Model ice-breaking tests for arctic operation are also being conducted and the stability of large ACV's is being investigated.

**KEYWORDS**

air cushion vehicles

**CLASSIFICATION**

Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Lawrie, C.J.R.<br>"Ice Control Structures and Floating Ice Booms"<br>19th Annual Meeting<br>Petroleum Society of CIM<br>Calgary, Alberta<br>May 6 - 10, 1968 | LA 68 |

**SUMMARY**

The development of the site for EXPO'67 has altered the river regime to the extent that there is a real danger of more severe ice jams and flooding in the future. For this reason, an Ice Control Structure was built in LaPrairie Basin. By controlling the movement of ice through and out of the LaPrairie Basin, the structure provides a means of compensating for the effects of the changed river regime. Located just upstream from Montreal where the St. Lawrence widens to form the LaPrairie Basin, the Ice Control Structure spans more than 2,000 m width of the river. Completed in 1965, the structure is essentially an elaborate type of floating boom.

Approximately 100 km downstream from Montreal, the St. Lawrence widens to form Lake St. Peter. Due to wind and wave action from passing ships, large areas of shoal ice break off and jam the channel opened by icebreakers. Floating log booms anchored to the lake bottom are being used experimentally to determine if this can be prevented.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice booms, ice control structures | Ice<br>Diversion |

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Lawrie, C.J.R.
"Ice Control Measures on the St. Lawrence River"
Eastern Snow Conference
Oswego, New York
February 1972

**NO.**

LA 72

**SUMMARY**

This paper reviews ice control measures which have been used on the 250-km reach of the lower St. Lawrence River between Montreal and Quebec City since 1906. Current ice control measures are also discussed briefly as well as research and development studies of ice problems along the St. Lawrence River.

**KEYWORDS**

icebreakers, ice booms, ice control structures

**CLASSIFICATION**

Ice Breaking
Ice
Diversion

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

LeCourt, E. J.
"Air Bubbler System Design for the 140-ft WYTM"
Arctec Report No. 202C-3
US Coast Guard
January 1976

**NO.**

LE 76

**SUMMARY**

The 42.7-m (140-ft) class of Coast Guard Cutters is equipped with an air bubbler hull lubrication system for ice breaking. The air bubbler system reduces ice friction against the cutter's hull plating. This report describes the air bubbler system on this class cutter, gives its operating characteristics, and its design history.

**KEYWORDS**

icebreakers, air bubblers

**CLASSIFICATION**

Ice Breaking
Ice
Suppression

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

LeCourt, E. J., J. W. Lewis, T. Kotras,
and J. C. Roth
"Mechanical Ice Cutter Design and Testing of
1/6th Scale Model"
Prepared for US Coast Guard Washington, DC,
by Arctec Inc.
Report No. CG-D-16-73
1973

**NO.**

LE 73

**SUMMARY**

This report is the last phase of the development of a one-sixth scale (7 m) model of a unique mechanical ice-cutting and ice-displacement concept for clearing ice-free channels at a full-scale target speed of 5 knots in 0.6 m of freshwater ice.

The mechanics of ice cutting are analyzed. The theoretical ice breaking and ice removing resistance is also modeled mathematically and scaling laws are included in the analysis.

Winter tests in 1973 in a Pennsylvania lake provided data on the operation of an ice traction system used to replace conventional marine propulsion. Full-scale performance is predicted and fullscale design is described.

**KEYWORDS**

ice cutting

**CLASSIFICATION**

Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

LeCourt, E. J. and R. P. Woclker
"Evaluation of Mechanical Ice Cutter Concept for Use in Domestic Ice Breaking Service"
National Technical Information Service
Rep. No. CG-D-59-74
US Department of Communications
1973

**NO.**

LE 73

**SUMMARY**

The mechanical ice cutter concept was successfully tested with a one-sixth scale model (Rep. No. CG-D-16-73, dated July 1973). It was shown that a mechanical ice cutter is a viable, effective and efficient system for clearing a channel of ice.

Included are evaluation studies for 5 different areas: the upper Mississippi River, the Illinois Waterway, the Alaska/Arctic region, the St. Lawrence Seaway and the east coast of the US. For each region or waterway, the ice conditions, traffic description, operational requirement of a mechanical ice cutter and benefits are presented. For the upper Mississippi River, a cost/benefit analysis is included as well.

The report recommends that a prototype MIC be constructed and deployed in the upper Mississippi River with the capability of clearing a 20-m wide channel on 0.3 m of ice at 5 km/h, cutting up to 1 m of ice, having a draft of less than 2 m and having an endurance of 1 week. Preliminary design information on the hull, ice cutters, machinery design and cost estimate are presented.

Appendix A of the report is an indepth study entitled "Evaluation of Ice Management Problems Associated with Operation of a Mechanical Ice Cutter on the Mississippi River". Climatic data, ice conditions and river temperatures and discharges are given for the Mississippi River. A detailed refreezing analysis of a cleared channel, generation and effects of brash ice, movements and accumulations of ice slabs, and the development of ice jams is presented.

In summary, the author indicates the use of a MIC and subsequent winter traffic will not increase the natural incidence of ice jam formation and may, in fact, actually reduce the occurrence of jamming by the presence of the cut channel.

**KEYWORDS**

ice cutting

**CLASSIFICATION**

Ice Breaking

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Legerer, F. J.
"Design Strategy for Ice Navigation"
Proc. Second POAC
pp 101 - 114
Iceland
1973

**NO.**

LE 73

**SUMMARY**

In this paper, the author discusses the cost effectiveness of various auxiliary methods of ice breaking. Ship-bound devices discussed include heeling tans, mechanical pitching systems, air lubrication systems, mechanical cutters, water jet devices and steam jet devices. For off-ship auxiliary methods, the author includes air bubblers, explosives, Hovercraft and barges. Relative operating efficiencies are calculated for the various devices and a formulation of the general problem of cost optimizing ice transportation was presented.

It was concluded that a low pressure steam jet device is likely to be the most promising auxiliary device available at this time.

**KEYWORDS**

icebreakers, ice cutting, air bubblers, explosives, ice navigation

**CLASSIFICATION**

Ice Breaking
Ice Suppression, Ice Removal

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Legerer, F. J.
"Improvement Potential of Ice Navigation"
N.A.T.O. Arctic Systems Workshop
1975

**NO.**

LE 75

**SUMMARY**

The paper suggests that substantial cost savings of up to 50 percent can be expected if design analysis of ice-breaking techniques is based on recent advances in applied mechanics. This cost saving could be realized by changing current design practices and arriving at new hull forms taking into account laminar boundary layer theory, multiphase fluid flow, impact theory and new construction methods. In addition, auxiliary devices and ice structural stability and ice force based steering equipment should be developed which would result in a reduced energy and financial demand.

**KEYWORDS**

ice navigation, icebreakers

**CLASSIFICATION**

Ice Breaking

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Lewis, E. L.
"Arctic Fjord Flushing"
Proc. of the Second International Conference
on Port and Ocean Engineering Under Arctic
Conditions
pp 223 - 237
Iceland
August 27 - 30, 1973

**NO.**

LE 73

**SUMMARY**

This short paper reviews what is known about the flushing or the outflow of fresh- and brackish water in ice-covered fjords in Norway. Freshwater from the spring melt of snow, summer melt of glaciers and sea ice melt tends to remain near the surface and flow outward. There must be some inflow of saline water from the sea, but it is not clear how much. The outflow can contribute to breakup of sea ice.

An estimate of the effort to understand this process is made.

**KEYWORDS**

flow developers

**CLASSIFICATION**

Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Lewis, J. W., N. A. Ehrlich and E. J. LeCourt<br>"Development of a Craft Capable of Preparing An Ice-Free Channel Through Solid Ice Cover"<br>2nd International Conference on Port and Ocean Engineering Under Arctic Conditions<br>Iceland<br>1973 | LE 73 |

**SUMMARY**

A program was initiated by the US Coast Guard to increase the channel clearing capability of icebreakers. One concept which has developed is the Mechanical Ice Cutter (MIC).

A one-sixth scale model was constructed and tested. Mechanical ice cutting equipment is used and the special shape of the underwater portions of the berth moves the ice slabs under the ice sheet at each side of the channel. Circular saws with carbide tips were used. The full-scale ice cutter is expected to clear a 15-m wide channel in freshwater ice 0.6 m thick at speeds of 4 - 5 knots.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice cutting, icebreakers | Ice Breaking |

AGRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Lewis, J. W. and R. P. Johnson<br>"St. Lawrence River All-Year Navigation Ice Control System"<br>US Department of Transportation<br>April 1980 | LE 80 |

**SUMMARY**

The objective of this study was to prepare designs and specifications for an ice control system which would allow all-year navigation in the Brockville to Cardinal section of the international portion of the St. Lawrence River. The study involved operation of a distorted scale (horizontal scale, 1:150; vertical scale, 1:60) hydraulic model of the section of the river extending from Stillwells Point, New York to Red Mills, New York. Three alternative ice control systems were tested under varying river flow rates and stages, and under varying ice conditions which included ice cover formation, consolidated ice covers, and spring breakup. A model ship was passed through the navigable booms and high winds were simulated. In conjunction with the mathematical models, the hydraulic model test results were used to assess the impact of the ice control systems on the generation of frazil ice and on the regulation of the river and Lake Ontario water levels. The preferred alternative system was designed based on the results of these analyses.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice navigation, ice booms | Ice<br>Diversion |

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Livingston, C. W.
"Explosions in Ice"
US Army Technical Report 75
December 1960

**NO.**

LI 60

**SUMMARY**

Tests were conducted during the summer of 1957 at the edge of the Greenland Ice Cap, near Camp Tuto, to supplement data from explosions in frozen ground and to obtain information for the development of criteria for the destruction and protection of structures in or on the ice. The tests included 24 instrumented and 106 uninstrumented blasts using 4 types of explosives in spherical charges weighing 1.1 - 18 kg and detonated above, in contact with, and at various depths below the ice surface. Measurements were made of under-ice pressure, crater dimensions, flyrock travel, and airblast pressures.

**KEYWORDS**

explosives

**CLASSIFICATION**

Ice Breaking

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

McDonald, A. F.
"Design of an LNG Terminal in Canada's High Arctic"
PORTS'80 Conference
pp 488 - 503
May 19 - 21, 1980

**NO.**

MC 80

**SUMMARY**

This paper provides general background to the LNG terminal being proposed for Bridport Inlet on Melville Island.

Included is a description of the ice management studies carried out by Acres Consulting Services Limited and NORDCO Limited for this project. They concluded that the most feasible system would be one that utilized cooling water effluent from the LNG refrigeration process. The heat rejected is calculated to limit ice growth to a 60-cm thickness in a 100 000-$m^2$ area at the dock face. The water effluent would be discharged from submerged nozzles and a 2-sided containment barrier or curtain will enhance.its effectiveness.

**KEYWORDS**
thermal discharges, harbour design

**CLASSIFICATION**
Harbour Ice
Ice
Suppression

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| McFadden, T.<br>"Suppression of Ice Fog from Cooling Ponds"<br>CRREL Report 76-43<br>1976 | MC 76 |

SUMMARY

Ice fog generated at the Eielson AFB power plant cooling pond contributes heavily to the total ice fog problem on the base. Several methods for ice fog suppression were studied and 2 techniques were tested experimentally. Experiments were also conducted to determine the magnitude of the various modes of heat transfer within the pond's microclimate. Values of evaporative and radiative heat loss during ice fog are presented. Ice cover is shown to be an effective ice fog suppression technique. Monomolecular films are also shown to be effective and offer some unique advantages, such as ease of application and lower overall cost. The heat normally lost to evaporation must be dissipated by other means during suppression. With the ice cover technique, this is accomplished by melting the ice cover. During suppression with monomolecular films, the heat must be dissipated by increasing radiative and convective losses. The simplicity of application of monomolecular films, along with their lower cost, combine to make this technique attractive; however, the lower pond temperatures and increased suppression effectiveness weigh heavily in favour of the ice cover technique. More exhaustive testing will provide a better understanding of the problems involved in using the ice cover method of suppression.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice fog | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Mellor, M.
"Snow Removal and Ice Control"
CRREL Report
April 1965

**NO.**

ME 65

**SUMMARY**

The state-of-the-art of snow removal and ice control up to April 1965 is presented. Physical characteristics of snow, and mechanical and thermal methods for its removal in typical applications on highways, mountain passes, city streets, railroads, and airfields are considered. Ice control methods by both mechanical and chemical melting are presented. Method costs, organization and planning of snow control work and highway design considerations are also included in the paper.

**KEYWORDS**

ice removal, chemicals

**CLASSIFICATION**

Ice Breaking
Ice
Suppression

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Mellor, M.
"Cutting Ice with Continuous Jets"
2nd International Symposium on Jet Cutting
Technology
Cambridge, England
April 2 - 4, 1974

**NO.**

ME 74

**SUMMARY**

The practicality of cutting ice with continuous water jets has been investigated by laboratory experiments and field tests, using nozzle pressures from 17.2 - 690 MN/m$^2$, traverse speeds from 0 - 1.8 m/s, and nozzle diameters from 0.203 - 0.584 mm. Special emphasis has been given to a study of the feasibility of using water jets to supplement the performance of ice-breaking vessels. While the "noncontact" aspect of a jet tool is attractive, power requirements for deep penetration at high traverse speeds are exorbitant by comparison with the power requirements for competing cutting systems. Application of test data in design calculation for other cutting applications is discussed.

**KEYWORDS**
ice cutting

**CLASSIFICATION**
Ice Breaking

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

|  |  |
|---|---|
| **SOURCE** | **NO.** |
| Mellor, M.<br>"Towing Ships Through Ice-Clogged Channels by Warping and Kedging"<br>CRREL Report 79-21<br>September 1979 | ME 79 |

**SUMMARY**

The report studies the question of whether Great Lakes freighters could move effectively through ice-clogged channels with the aid of tows provided by warping or kedging systems. Ten operational concepts are outlined, and their advantages and disadvantages are noted. The crushing resistance of floating brash ice is then analyzed. The neutral, active and passive states of stress for laterally confined brash ice are considered, and the resistance to horizontal thrusting by a smooth vertical wall is calculated for cohesionless brash ice, and for ice in which there is finite cohesion between the ice fragments. The thickening of the ice cover in the vicinity of a "pusher", and the formation of pressure ridges, are analyzed in order to estimate the amount of pileup that can occur against a ship hull. The analysis then moves on to consideration of ship resistance by brash ice, taking into account crushing resistance at the bow, tangential friction at the bow, and hull friction aft of the bow section. Comparisons are made between thrust from the ship's screws and the calculated ice resistance. The next section of the report estimates the force requirements for a warping or kedging system in terms of thrust augmentation for existing vessels. Tow cable requirements are given, and estimates are made for cable anchors and for anchorage of underwater structures. The force and power requirements for winches and windlasses are given, the practical problems involved in the pickup or transfer of cables are mentioned, and the report concludes with a brief appraisal. The conclusion is that a simple warping tug system is appropriate for a full-scale experiment, a chain ferry with auxiliary barge seems attractive for an operational system, and a chain ferry plow may be an efficient way to clear ice from channels.

|  |  |
|---|---|
| **KEYWORDS** | **CLASSIFICATION** |
| ice navigation | Ice<br>Navigation |

AGRES TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Mellor, M.<br>"Icebreaking Concepts"<br>CRREL Special Report 80-2<br>January 1980 | ME 80 |

**SUMMARY**

Ice-breaking concepts that have potential application in the protection of offshore structures and drillships are reviewed. The concepts dealt with include conventional ice breaking by ships, ice breaking by air cushion vehicles, breaking against fixed structures, mechanical cutting with drag bit tools, blasting by high explosives, blasting with compressed gases or propellants, ice melting, thermal cutting, cutting with lasers, cutting with high pressure water jets, and unproven novel concepts. Special emphasis is given to the specific energy requirements for the various methods.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers, air cushion vehicles, ice cutting, explosives | Ice Breaking |

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Mellor, M.
"Ship Resistance in Thick Brash Ice"
Cold Regions Science and Technology
Vol 3, pp 305 - 321
1980

**NO.**

ME 80

**SUMMARY**

The mechanical properties of thick brash ice are considered, with special emphasis on the friction angle diameter for a linear Mohr-Coulomb failure criterion. The static equilibrium of a uniform brash layer is discussed, and the internal stresses are given for neutral, active and passive stress states. Horizontal displacement of brash by a smooth vertical plate is analyzed, and the crushing forces for plastic yielding in the passive stress state are deduced for cohesionless brash and for ice that has finite internal cohesion.

For ships which tend to have shaft power proportional to the cube of the beam, the limiting ice thickness is directly proportional to the beam. Using the very limited data on mechanical properties of brash ice and assuming that the propellers continue to function well, the estimates indicate that a Great Lakes bulk carrier would be near its limit of movement when the brash thickness in a wide channel is about 10 percent of the beam, while an icebreaker in salt water brash could perhaps keep moving until the brash thickness reached about 20 percent of the ship's beam.

The above estimate assumes that brash ice is cohesionless. If there is significant cohesion the thickness of ice needed to stop a ship will be less. The relative importance of cohesion decreases as the layer thickness increases and vice versa.

**KEYWORDS**

icebreakers

**CLASSIFICATION**

Ice Breaking

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Mellor, M., G. P. Vance, J. L. Wuebben and
G. E. Frankenstein
"An Investigation of Ice Clogged Channels in
the St. Mary's River"
USA CRREL, Report CG-D-22-78
Hanover, New Hampshire
March 1978

**NO.**

ME 78

**SUMMARY**

It is estimated to cost $1,250,000/km annually to keep a channel in the St. Mary's River relatively clear of ice. This figure includes capital, operating and maintenance costs.

It appears the most economical solutions lie in rafting the ice to a disposal area, plowing the ice under the ice sheet, and ejection of the ice to the top of the ice sheet.

**KEYWORDS**

ice removal

**CLASSIFICATION**

Ice
Navigation

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Michel, B.<br>"Off-Shore Mooring Structure for the Arctic"<br>IAHR Symposium, Ice and Its Action on Hydraulic Structures<br>Reykjavik, Iceland<br>1970 | MI 70 |

**SUMMARY**

This paper presents a new type of design for a harbour that will shelter ships in the Arctic Ocean. The ships will be protected against moving ice regardless of the direction of ice drift. The mooring structure is cylindrical in shape and is to be set off-shore in deep waters to receive one, two or more of the largest possible tankers. One main feature of this new structure is the fact that it clears ice on its side so that no ice accumulation will form around it.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Michel, B.
"Ice Management in Hydraulic Design - Recent Canadian Experience"
IAHR Symposium, Ice and Its Action on Hydraulic Structures
Leningrad
1972

**NO.**

MI 72

**SUMMARY**

Three recent examples of ice management for major Canadian projects are discussed in the paper. However, the references are entirely to river ice problems. Ice management consists mainly of control structures and icebreakers.

**KEYWORDS**

icebreakers, ice control structures

**CLASSIFICATION**

Ice Breaking
Ice
Diversion

AGRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Michel, D. and D. Berenger<br>"Algorithm for Accelerated Growth of Ice in a Ship's Track"<br>3rd International Symposium on Ice Problems<br>Hanover<br>1975 | MI 75 |

**SUMMARY**

One of the major problems of winter navigation in closed channels or quiescent water bodies is the accelerated growth of ice in a limited ship's track with repeated ship passages. Because of the presence of water close to the surface in the holes of broken-up ice accumulations, this growth may lead to unusual thickening of the ice that would eventually close the passage to further navigation, unless the large volume of ice is cleared by some means.

The authors have developed an algorithm to represent this phenomenon for navigation close to a wharf in Arctic waters.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice navigation | Harbour Ice |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Noble, P., R. Abdelnour and D. Miller<br>"Physical Simulation of Ice Behaviour at an Arctic Ship Terminal"<br>IAHR Symposium on Ice Problems<br>pp 129 - 157<br>Lulea, Sweden<br>August 1978 | NO 78 |

SUMMARY

It was decided that physical simulation of LNG ships entering a proposed terminal at Bridport Inlet over a winter period would provide useful insight into problems that might interfere with continuous operation of the terminal.

The model test program showed that a terminal in Bridport Inlet cannot operate through the whole winter season without some assistance being given to the LNG ships. The LNG ships will have some problems while entering the terminal and docking in the berthing area, whether using ahead or astern modes of penetration.

As an optimal solution, the tests suggest entering ahead until the end of December to provide a straight channel, then entering astern for the remaining winter season. This will fix a well-defined channel in the first 3 mo after freezeup, without accumulating excessive ice in the berthing area.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice navigation | Harbour Ice |

AGRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Paige, R. A.<br>"McMurdo Ice Wharf-Physical Characteristics and Criteria for Protection"<br>Naval and Civil Engineering Laboratory<br>Port Hueneme<br>1969 | PA 69 |

**SUMMARY**

Since January 1964, fast ice along the western shore of Winter Quarters Bay near McMurdo Station has been used with a great deal of success as a wharf for ship unloading. Prior to that time, ships were offloaded onto the annual sea ice several kilometres from the station, a dangerous and time-consuming operation. Because of the importance of this facility, investigations were begun in Deep Freeze 66 (DF-66) to determine the extent and properties of the ice wharf and to develop criteria for possible protective measures. Based on this investigation, it was concluded that use of the natural ice wharf at McMurdo will be severely curtailed by DF-72 if measures are not taken immediately to prevent further loss of the fast ice. A protective dock has been designed by the Naval Facilities Engineering Command (NAVFAC) that will cover the face of the ice wharf to protect the ice from wave action; however, early construction of this dock is essential to prevent further loss of the fast ice. Once protected from wave action and uncontrolled drainage, the internal temperatures of the ice wharf are sufficiently low to prevent any extensive melting and deterioration.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice forces, harbour design | Harbour Ice |

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Partenov, A. F., V. V. Balanin and L. V. Ivanov
"Effect of Ice on Ships and Structures and
Maintenance of Their Operation at Sub-Zero
Air Temperatures"
23rd International Navigation Conference, Section II
Ottawa
1973

**NO.**

PA 73

**SUMMARY**

This paper presents a comprehensive report on the developments in Russia for the past 15 years concerning principal problems encountered, trends in ice-control methods, design of ice-control facilities, and experience gained in combating ice.

The main obstacle to movements within a port is the ice cover which is repeatedly broken by ships, and owing to the emergence of hummocks, grows rapidly in thickness. The ice cover and fast ice at piers also makes berthing difficult.

Several methods of ice management are discussed. Where there exists sufficient thermal stratification across the depth of a basin (temperature difference greater that 0.5°C), the utilization of deep water heat is most economical. It can be done with pneumatic installations, and flow generators. Some empirical relations for width of an ice-free lane, and the air consumption required, are presented.

The proper location of hot water sources, such as thermal power stations, is considered of great importance. Warm water can be used more effectively if it can be released from perforated pipes laid beneath the area where ice formation is to be prevented. A system has been developed which ejects a steam-air mixture from perforated pipes placed underwater. It operates most economically when a 0.05- to 0.1-m ice cover is retained. Automatic control can be provided for the system. Full-scale experiments with creation and maintenance of ice-free water areas were carried out in the mouth of the Dvina River, and some are still continued in the Vanino Harbour.

Application of antifreeze films and foaming compounds for the insulation of water surfaces is limited because of a uniform thickness can only be maintained for a short time and is inefficient at low temperatures.

(cont'd)

**KEYWORDS**

air bubblers, flow developers, insulation,
thermal discharges

**CLASSIFICATION**

Ice
Suppression

**SOURCE**

**NO.**

PA 73
(cont'd)

**SUMMARY**

Protective and insulating coatings have been applied to the surface of some structures with success. These consist of floating boxes filled with foamed polystyrene.

Old aircraft engines have been found to be useful power sources for combating ice in a harbour area. The hot exhaust gases can be used to prevent icing of fenders, damping devices, pier walls, and moving elements of structures, as well as maintaining areas of water in ice-free conditions.

**KEYWORDS**

air bubblers, flow developers, insulation, thermal discharges

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Parker, W. B.<br>"Marine Transportation in Alaska's Bering Sea and Arctic Ocean Areas"<br>1st International Conference, Port and Ocean Engineering Under Arctic Conditions<br>Norway<br>1971 | PA 71 |

**SUMMARY**

The paper discusses the development of marine transportation in Alaska in a general manner.

The major problems that must be overcome for developing offshore terminals in this area appear at present

-protection of loading ships from moving ice pack
-protecting pipelines from ice scour
-elimination of ice pile-up on offshore structures.

No ice management techniques are discussed.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice problems | Harbour Ice |

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Parsons, R. C. and R. M. Hopkins
"A Chemical Method for Ice Destruction"
4th International Conference on Port and Ocean
Engineering Under Arctic Conditions
1977

**NO.**
PA 77

**SUMMARY**

A novel method for ice destruction is described in which ice is reacted with such gases as ammonia, hydrogen chloride, sulphur dioxide or volatized ammonium chloride. The associated equipment to deliver these reactants to the ice is very simple consisting only of nozzles, tanks, pressure regulating valves and hose. Using this equipment and ammonia as a reactant gas, drilling rates up to 210 cm/min have been achieved. Because of the "salting effect" which occurs when the reactant gas dissolves in the melt water, refreezing is minimized. A wide range of applications for the method have been identified. These include drilling in icebergs for the placing of explosive charges or for the setting of anchor bolts for towing, deicing of ship superstructures, deicing of canal locks and the reduction of friction between the hull of an icebreaker and the ice surface.

**KEYWORDS**
chemicals

**CLASSIFICATION**
Ice Breaking

AGRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Perdichizzi, P. E. and T. Yasuda
"Port of Anchorage Marine Terminal Design"
ASCE Applied Techniques for Cold Environments
Cold Regions Specialty Conference
Alaska
May 17 - 19, 1978

**NO.**

PE 78

**SUMMARY**

Engineering design is complicated by severe ice conditions at the Port of Anchorage. Ice builds up like thick layer cake on every pile supporting the wharf until connecting cakes form a nonuniform honeycomb under the entire structure. Extreme tidal fluctuations create this condition. The rush of incoming tide waters carry another hazard. The strong currents push thick ice floes against the port facilities. Opening the port for winter operation in 1964 allowed, for the first time, direct transport of supplies to Anchorage and the interior of Alaska on a year-round basis. Supported by a pile system which incorporates batter piles, this wharf was one of the few structures to survive the largest North American earthquake recorded that destroyed other routes to Anchorage in 1964. Since then the structures have repeatedly demonstrated the ability to survive nature.

**KEYWORDS**
harbour design

**CLASSIFICATION**
Harbour Ice

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Perham, R. E.
"Forces Generated in Ice Boom Structures"
CRREL Special Report 200
January 1974

**NO.**

PE 74

**SUMMARY**

Two ice booms in the international section of the St. Lawrence Seaway, near Ogdensburg, New York, were instrumented for measuring ice forces in the winter of 1972/73. These ice booms are among several installed annually by the United States and Canada primarily to prevent ice jams from forming and severely restricting water flows. As presently used, they act as barriers to the navigation of ships. Measurements were initiated at a shore anchor site. The system used for these measurements consisted of a commercial tension cell, located in a new line spliced to the anchor rope, which provided electrical signals to a strip chart recorder that operated continuously. A second system consisted primarily of 2 special tension cells, an armored signal cable, a direct conversion electric generator, and a recorder. This system was used to measure 2 concurrent forces at a midstream location where high loads were expected. Additional information on such influencial factors as water velocity, ice thickness, wind conditions and air temperature was also obtained.

**KEYWORDS**

ice booms, ice forces

**CLASSIFICATION**

Ice
Diversion

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Perham, R. E.
"Some Economic Benefits of Ice Booms"
2nd International Symposium on Cold Regions Engineering
University of Alaska
1976

**NO.**

PE 76

**SUMMARY**

The cost of these ice control devices over the past 17 years have ranged from about $156 - $1,094/m with one set costing approximately $1,500,000. The value of many ice booms can best be related to the cost of replacing the electric power that could be lost if they were not present, as opposed to trying to choose a cost basis for a flood. A rough estimate of $0.01/kW·h for the value of replacement power is used here. The most valuable ice boom could be the Lake Erie ice boom which saves an estimated $13,000,000/year. Next are the ice booms on the Beauharnois Canal which are used with particular operating techniques to save approximately $4,300,000/year. Ice booms can also help save millions in shipping costs as well by stopping excessive ice movements during the navigation season in winter on the Great Lakes.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

AGRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Perham, R. E.
"Ice and Ship Effects on the St. Mary's River
Ice Booms"
Proc. 3rd National Hydrotechnical Conference
Canadian Society Civil Engineering
pp 419 - 433
Quebec
May 30 and 31, 1977

**NO.**

PE 77

**SUMMARY**

The St. Mary's River connects Lake Superior with Lake Huron. It contains many navigation improvements which make it an important commercial shipping route. The operation of ships in winter under a federal program to extend the navigation season has led to troublesome ice movements and accumulations. To help counteract these effects, 2 ice booms with a 76-m wide navigation opening between their adjacent ends were installed at the southerly outlet from the harbour at Sault Ste. Marie, Michigan and Ontario

The ice booms contained 6 force measuring devices. Records of these forces and pertinent data on the weather, water levels, ship passages and ice conditions were kept the following winter of 1975/76.

The ice booms reduced the harbour ice losses to an acceptable level and provided much information about the interactions between ice booms, the ice cover and ships. Ships and environmental effects kept the ice behind the west boom free from shore much of the winter. The maximum in the east boom was an impact load of about 712 kN. The forces associated with ship passages averaged 111 kN.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Perham, R. E.
"Performance of the St. Mary's River Ice Booms"
CRREL Report 78-24
1978

**NO.**

PE 78

**SUMMARY**

The ice booms on the St. Mary's River at Sault Ste. Marie, Michigan and Ontario, were operated a second winter, 1976/77, under colder conditions, with less water flow, lower water levels, and 25 percent fewer ships in the river than during the previous year. The ice cover behind the booms remained frozen to shore for longer periods, and the loads registered in the booms were relatively unaffected by ship passages compared with the previous year's activity. As in the previous year, most structural load changes took place in the west ice boom and were due to movements of the ice cover immediately upstream from the boom. The cover broke free from shore on 3 occasions; the first and third occasions were minor events, but on the second occasion the cover cracked free and the timbers remained frozen.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

ACRES

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Peschanskiy, I.<br>"Breaking The Russian Ice"<br>New Scientist<br>Vol 41, p 574<br>March 13, 1969 | PE 69 |

SUMMARY

The author briefly describes several methods of ice management currently being used in the USSR. Dusting the ice with coal dust to lower the surface albedo and air bubbling are mentioned. Brief mention is made of successful testing with a model of a mechanical ice cutter which cuts and deposits the ice on top of the ice on either side of the track. A hydraulic cutter using a high-pressure water jet to cut the ice is also mentioned. The cut ice is then directed under the adjacent ice, leaving a clear channel behind the vessel.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice cutting, air bubblers, ice dusting | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Peschanskiy, I. S.<br>"Methods of Disrupting an Ice Cover"<br>Ledovedeniye i Ledotekhnika (Ice Science and Ice Technology)<br>Chapter VI, pp 308 - 367<br>(Available from NTIS)<br>Leningrad<br>1967 | PE 67 |

**SUMMARY**

This report provides a general review of ice control techniques, i.e., icebreakers, ice cutting machines, ice blasting, and thermal methods (electric heat cutting, dusting with various materials, and use of air bubbler systems to raise deep warm water to the surface).

Examples of practical applications for breaking ice are provided. Experience with ice blasting techniques, dusting, and air bubbler systems are described.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers, ice cutting, explosives, ice dusting, air bubblers, thermal discharges | Ice Breaking<br>Ice Suppression |

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Petroleum Engineer International
"Air-Cushion Vehicle Tested on North Slope"
pp 17, 20
March 1982

**NO.**

PE 82

**SUMMARY**

Tests conducted at Prudhoe Bay, Alaska, during the winter of 1981/82 indicate that an air cushion vehicle, the ACT-100, is successfully performing as an icebreaker. This may enable oil companies to operate drilling rigs for an additional 60 days each year in the Beaufort Sea.

The Beaufort Sea along Alaska's north slope is relatively ice-free along the shoreline for only 1-1/2 months each year. As a result, supplies for offshore islands and platforms often remain stockpiled on shore for long periods.

The ACT-100 is not moved at high speeds by propellers. Instead, it relies on other vehicles or winch lines for propulsion up to 17 km/h. This allows it to operate on land or sea with maximum cargo capacity. Propulsion for these tests was provided by a shallow-draught tugboat, the Arctic Fox.

**KEYWORDS**

air cushion vehicles

**CLASSIFICATION**

Ice Breaking

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Pounder, E. R.
"Thermodynamic Considerations on the Use of Air Bubbling Systems in Salt Water"
Proc. of the Symposium on Air Bubbling
Ottawa
1961

**NO.**

PO 61

**SUMMARY**

Air bubbling systems have been very successful in preventing ice formation in local areas in freshwater lakes and rivers. The principle of the method is to mix warmer water from appreciable depths with surface water to supply the necessary heat. The availability of warmer water depends on the existence of a density inversion temperature of 4°C in pure water, leading to thermocline formation. If salts, in the proportions found in the oceans, are dissolved in water, both the temperature decreases more rapidly with increasing concentration becoming equal to the freezing point of -1.3°C for a salinity of 24.7 parts per thousand. For salinities greater than this figure, a density thermocline will not form, and a still body of salt water cooled by the air will develop convective circulation to maintain a uniform temperature right to the bottom.

These considerations suggest that air bubbling could serve no purpose in sea water. Nevertheless, a few experimental installations, such as Operation Polynya at Thule, have shown that air bubbling in salt water can retard or prevent ice formation and even melt an ice cover which has formed. In the Thule experiments, the water temperature showed no increase with depth, in agreement with the discussion above.

**KEYWORDS**

air bubblers

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Pratte, B. D.
"The Churchill River Salt-Water Tidal Model"
National Research Council of Canada, Hydraulics Laboratory Technical Report
February 1977

**NO.**

PR 77

**SUMMARY**

Results are presented of tests on a salt-water tidal model of the lower estuary of the Churchill River on Hudson Bay. The Port of Churchill is forced to close after mid-October by ice forming in the rapids upstream which sweeps through the harbour and severely hinders shipping operations at the dock.

To protect the ships and allow extension of the shipping season, various deflector piers were tested and a complete dam and spillway was tried. The deflector was found to be useful in giving protection from ice and currents in the harbour, and not to cause an unacceptably high rate of sediment accumulation. While a dam and spillway would be very costly to construct, it would keep river ice upstream, produce a quiet harbour, provide opportunities for development and tourism, and also a close source of freshwater for the town.

**KEYWORDS**

structures

**CLASSIFICATION**

Ice
Navigation
Ice
Diversion

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Quinn, F. H., R. A. Assel, and D. W. Gaskill<br>"An Evaluation of Climatic Impact of the Niagara Ice Boom Relative to Air and Water Temperature and Winter Severity"<br>NOAA Technical Memorial ERL GLERC-30<br>August 1980 | QU 80 |

**SUMMARY**

The objective of this study was to determine if the Niagara River ice boom installed every winter since 1964/65 has prolonged the Lake Erie ice cover at Buffalo, New York, resulting in significant changes in the spring warm-up of Lake Erie and longer, colder winters in the area.

On the basis of the analysis presented in this report, there is no evidence that the operation of the ice boom has either extended Buffalo winters or made them more severe.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice booms | Ice<br>Diversion |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Rekonen, T.
"Effects of Ice on Navigation and on Navigational Aids"
23rd International Navigation Conference, Section II
Ottawa
1973

**NO.**

RE 73

**SUMMARY**

The paper reports on the effects of ice on navigation and marine structures in Finland.

Ice formation starts from the coast, proceeds to islands near the coast, to the point of the islands, and then out to the open sea. This inland zone then remains land-fast for the season. A zone of pack ice is frequently formed at the edge of the solid ice which poses the most difficult obstacle to winter traffic.

The thickness of ice in the island zone varies from 0.5 - 1.0 m. Ports are kept open as long as possible by icebreaker assistance. It is reported that ship channels made in solid ice stay open even under the worst wind conditions. No mention is made of ice management techniques within harbours.

**KEYWORDS**

ice navigation, icebreakers

**CLASSIFICATION**

Ice
Navigation

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Robillard, L.
"Suppression de la Couverture de Glace Par un
Rejet Thermique"
Canadian Journal Civil Engineering
Vol 5, pp 53 - 57
1978

**NO.**

RO 78

**SUMMARY**

The thermal discharges from various sources that occur during winter may prevent ice formation at the free surface. In order to predict the extent of the free surface without ice, numerical models of thermal discharges should take into account

-the particular heat transfer at the free surface that occurs during winter time

-the nonlinear relationship between density and temperature for water near 0°C.

This article indicates a method of modifying existing models and presents some results obtained from a modified buoyant surface jet model.

**KEYWORDS**

thermal discharges

**CLASSIFICATION**

Ice
Suppression

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Sadler, H. E. and H. V. Serson
"Ice-Free Berths for Loading Ships in the Arctic"
Oceans'80 International Forum on Ocean Engineering in the 80's
Published by IEEE
Seattle, Washington
September 8 - 10, 1980

**NO.**

SA 80

**SUMMARY**

The paper suggests that the buoyancy forces on freshwater at the surface of the sea or immediately below the surface of the ice permit the use of this freshwater as an efficient means of transferring heat energy to the sea ice, to melt it or to prevent its formation. The source of heat may be found in the lower levels of freshwater lakes, in waste heat from industrial processes, or in the combustion of fuel in a heater. The design of a plant to carry out this process presents no new problems to the engineer and the system may be made self-regulating. Installation costs will vary with local conditions but should be at least one order of magnitude less than those involved in building an oil loading facility offshore.

**KEYWORDS**

thermal discharges, flow developers

**CLASSIFICATION**

Ice
Suppression

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Saunders, T. F.
"A Cold Canadian Port Development"
3rd International Ocean Development Conference
Tokyo
August 1975

**NO.**

SA 75

**SUMMARY**

The paper describes the port development of the most northerly asbestos mine in Canada. The port at Deception Bay in Hudson Strait is used to ship out the mine product and bring in the essential fuel and supplies within an annual 3-mo ice-free shipping period.

The wharf is designed to accommodate and load ore carriers of 50 000 dwt and unload small cargo vessels of 1,500 dwt. The construction consists of 21.3 m diameter sheet-pile cells which are approximately 22.9 m high. Ice thickness in the bay is predicted to be about 1.2 m.

No ice management techniques are mentioned.

**KEYWORDS**
harbour design

**CLASSIFICATION**
Harbour Ice

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Saunders, T. F. and M. Timascheff
"Ice Effects on Planning, Design, and Operation of a Major Oil Terminal"
23rd International Navigation Congress
Ottawa
1973

**NO.**

SA 73

**SUMMARY**

A marine terminal has been constructed on the south shore of the St. Lawrence River opposite Quebec City. It is designed to receive crude oil from tankers in the 100 000 dwt class. Ice floes up to 75 cm thick were anticipated, with velocity up to 2 m/s in tidal currents. The tidal range is approximately 6 m.

Ice deflector cells were incorporated in the design to protect vessels and the wharf head against ice floes. Tugs push out loose ice.

**KEYWORDS**

harbour design

**CLASSIFICATION**

Harbour Ice

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Shvaishtein, Z. I.<br>"Cutting Ice with a Continuous High-Pressure Water Jet"<br>CRREL<br>Draft Translation 397<br>August 1973 | SH 73 |

SUMMARY

In a study of the possible techniques of cutting ice by an "icebreaker", it was clarified that, in addition to the mechanical devices for cutting and breaking down the ice, it is feasible to utilize a high-pressure water jet. The possibility of the utilization of such jets is particularly important for cutting relatively thick ice (from 0.5 m or more) since the mechanical means (disk cutter, etc) are fairly complicated. During movement of the icebreaker, a hydro-compressor mounted on the ship feeds continuous high-pressure jets through shaped nozzles to cut a number of parallel blocks.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice cutting | Ice Breaking |

**ACRES**

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Skaerbo, O. and P. V. Jespersen
"Harbours in Greenland"
1st International Conference, Port and Ocean
Engineering Under Arctic Conditions
Norway
1971

**NO.**

SK 71

**SUMMARY**

Descriptive data on Greenland harbours includes climate, ice conditions, tidal ranges, navigation, and harbour construction.

The climate has many contrasts, since the island is influenced by both the Atlantic Ocean and the Arctic Ocean. Storm frequency is high and wind loads are important in marine construction. Tidal ranges are a maximum of 5.1 m.

Ice conditions consist of polar ice, drift ice, fast ice and glacier ice. Of interest is the fast ice which is formed in the fjords and along the coast. From Egedesminde and north the harbours are closed by fast ice for about 6 mo each winter. Thule is closed 8 mo. Most harbours appear to be constructed in active ice zones, and no mention is made of ice management techniques to extend the navigation season.

**KEYWORDS**

harbour design

**CLASSIFICATION**

Harbour Ice

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Snoke, M. D., Col.
"Winter Navigation Program - A Progress Report"
Great Lakes - St. Lawrence Seaway Winter Navigation Seminar
Detroit
1972

**NO.**

SN 72

**SUMMARY**

A progress report was given on means of extending winter navigation on the Great Lakes and St. Lawrence Seaway.

The following projects, supervised by the Corps of Engineers, are or particular interest.

1. Air Bubbler for White Fish Bay
2. Air Bubbler for Sugar Island Ferry Dock
3. Air Bubbler in Lime Island Ship Channel
4. Air Bubbler in Duluth Superior Harbour
5. Environmental Study of Waste Heat Melting Ice (Bay City, Michigan)

**KEYWORDS**
air bubblers, thermal discharges,
ice navigation

**CLASSIFICATION**
Ice
Suppression

AGRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| "A Symposium of Ice Breaking and Related Technologies"<br>Proc. of IceTech '75<br>Society of Naval Architects and Marine Engineers<br>April 1975 | SO 75 |

SUMMARY

The proceedings provide many interesting and informative papers on ship resistance in ice, icebreaker design, piering and displacement, low friction surface, scaling for modeling in ice, sea ice ridging and deformation, mechanical properties of ice, and ice-breaking technologies.

| KEYWORDS | CLASSIFICATION |
|---|---|
| icebreakers, coatings | Ice Breaking |

ACRES

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Sorensen, J.
"Dome's Beaufort Breakout"
Canadian Petroleum
pp 28 - 29
June 1979

**NO.**

SO 79

**SUMMARY**

Canmar's newest drilling ship bound for the Arctic is Explorer No. 4. It is being fitted with a bubbler system (a series of holes through which compressed air is forced) below the waterline of the hull. The bubbling action is expected to keep ice from forming near the vessel and reduce friction.

**KEYWORDS**

icebreakers

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Stehle, N. S.<br>"The McMurdo Ice Wharf"<br>Proc. of the Symposium on Cold Regions Engineering<br>Alaska<br>1971 | ST 71 |

SUMMARY

Since January 1964, fast ice along the western shore of Winter Quarters Bay near McMurdo Station, Antarctica has been used with a great deal of success as a wharf for ship unloading. H-piles are driven in the ice to anchor a cantilevered dock face to protect the ice wharf from wave action.

It appears that an entrance channel was cut into the fast ice, although the article does not say how this was done, or how it is being maintained.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice |

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Sydor, M., B. O. Krogstud and T. O. Odlaug
"Evaluation of Bubbler System for Winter
Navigation"
University of Minnesota (Duluth)
US Army Corps of Engineers
July 15, 1974

**NO.**

SY 74

**SUMMARY**

Installation of a winter shipping demonstration bubbler for the 1973/74 season began on December 5, 1973 in the Howards Bay area of the Duluth-Superior Harbor. Part of the bubbler was laid in Howards Pocket where little natural currents were present except seiching of the lake. This presented a condition for monitoring effects on the environment due to the bubbler.

Physical and chemical changes to the environment were small, although the effect of these changes on living organisms may be too subtle to measure on a short-term basis. Variations in bottom temperature and conductivity throughout the bay appeared to be greater than any changes produced by the bubbler alone.

**KEYWORDS**

air bubblers, ice navigation

**CLASSIFICATION**

Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Transportation Research Board
National Academy of Sciences
"Marine Systems in Frigid Environments"
Special Bibliography
March 1978

**NO.**

TR 78

**SUMMARY**

This bibliography contains abstracts of selected reports and journal articles that cover the range of problems associated with marine systems that operate in ice-covered waters.

Since the major emphasis of this material is on marine transportation rather than marine structures, many abstracts are on ice-breaking methods. There is also mention, however, of air bubbler systems to suppress ice, mechanical ice cutting methods and arctic terminal design considerations.

**KEYWORDS**
ice forces, icebreakers, ice cutting, air bubblers

**CLASSIFICATION**
Ice Breaking
Harbour Ice
Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Tsang, G.
"Fin Boom Ice Gate for Ice Control and
Winter Navigation"
IAHR - International Symposium on Ice
pp 492 - 502
Quebec City
July 1981

**NO.**

TS 81

**SUMMARY**

While conventional floating booms are effective, they present barriers to the channel and make winter navigation difficult. In addition, since removal and reinstallation of a conventional floating boom is a time consuming process, and at times even dangerous, it is not an ideal apparatus for controlling the retention and discharge of ice that accumulates in front of the boom. It would be very ideal if a gate could be provided to a conventional boom which can be opened and closed easily to facilitate winter shipping and for ice discharge and retention control.

A finned boom was developed by Tsang and Vanderkooy (1979), originally for the purpose of recovering spilled oil from ice infested rivers. Figure 1 is a photograph showing the field test of a prototype of the boom. It is seen from the picture that the ice-oil boom consists of a rigid perforated boom barrier and a number of fins or rudders behind the boom. The angle between the boom and the current can be varied by controlling the angle between the fins and the boom with cables. When ice floes and oil slicks drift to the boom, ice floes can be deflected to the outer side and the oil slicks flowed through the perforated openings to the downstream side of the boom, to be deflected by the fins to the shore for recovery. The ice-oil boom, or the fin boom as it now may be called, is stable enough to allow workers to remain standing on the boom while large ice floes are being deflected to the outside. It is proposed that fin booms be used to provide the desired gates to conventional floating booms. A gate can be formed by placing 2 mirror symmetric fin booms to an opening of a conventional floating boom. The V formed by the 2 fin booms can be opened and closed by manipulating the fin angles.

**KEYWORDS**

ice booms, ice control structures, ice navigation

**CLASSIFICATION**

Ice
Diversion

# TRANSPORTATION DEVELOPMENT CENTRE
# ICE CONTROL-ARCTIC PORTS AND HARBOURS
# REFERENCE SUMMARY

**SOURCE**

Vance, G. P.
"Analysis of the Performance of a 140-Foot Great Lakes Icebreaker: USCG Katmai Bay"
CRREL Report 80-8
February 1980

**NO.**

VA 80

**SUMMARY**

This report presents the results of the tests on the new US Coast Guard 42.7-m icebreaker Katmai Bay (WTGB-101) in the level plate ice and brash ice in Whitefish Bay and the St. Mary's River. The results indicate that the vessel can penetrate 55 cm of level freshwater ice with 5 - 8 cm of snow cover. It can also penetrate up to 122 cm of brash ice in a continuous mode and at least 76 cm of plate ice by backing and ramming. The installed bubbler system decreased the required power of the vessel from 10 - 30 percent in brash ice and 25 - 35 percent in level ice. The low friction coating appears to be effective in decreasing the friction factor when it remains intact; when it peels off it appears to make conditions worse than plain paint. An average dynamic friction factor of 0.15 could be used over the entire hull for these tests.

**KEYWORDS**

icebreakers, coatings

**CLASSIFICATION**

Ice Breaking

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Vance, G. P.
"Clearing Ice - Clogged Shipping Channels"
CRREL Report 80-28
December 1980

**NO.**

VA 80

**SUMMARY**

This report investigates the feasibility of clearing ice from the shipping channel of the St. Mary's River. Four basic concepts are investigated

-disposal under the ice
-disposal on top of the ice
-slurrying
-rafting.

Each technique was found to have application in limited portions of the river with the exception of disposal on top of the adjacent ice sheet, which is deemed feasible throughout the river system. Disposal onto the adjacent ice sheet will increase the free stream velocity less than 30.5 cm/s and raise the water level less than 0.30 m. Further model and field tests are recommended to validate the findings of this report.

**KEYWORDS**

ice removal

**CLASSIFICATION**

Ice Removal

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Vinogradov, O. G., J.A.C. Kentfield and
P. J. Vermeulen
"Ice Breaking Mechanisms for Ice Breakers and
Offshore Structures"
International Conference on Port and Ocean
Engineering Under Arctic Conditions
pp 1,069 - 1,079
1979

**NO.**

VI 79

**SUMMARY**

Improvements in icebreaking with application to ship icebreakers, offshore drilling platforms and other structures interacting with ice are described. A special lever mechanism for ship icebreakers or barrier structures for protecting drilling platforms is described where the horizontal force which the icebreaker creates or which acts on the structure is thereby substantially reduced.

Small scale prototypes were built and tested in order to prove the concept. Some comparison with the convectional technique of icebreaking was done. The results so far obtained confirm the concept and show that a lever mechanism breaks ice more efficiently than conventional techniques.

**KEYWORDS**

icebreakers

**CLASSIFICATION**

Ice Breaking

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Wade, R. G.
"A Demonstration of Shipment, Assembly and Operation of an Air Cushion Icebreaking Platform for Potential Support of Extended Shipping Seasons at a Remote Harbour"
Canadian Coast Guard
Ottawa
1978

**NO.**

WA 78

**SUMMARY**

The air cushion ice-breaking platform (HL-301) was transported to the Port of Churchill in a dismantled condition from Montreal on 2 standard CN flat cars. The objective was to operate HL-301 at Churchill in support of MV Arctic and its escorting icebreaker while berthing and manoeuvering after the end of the normal shipping season.

HL-301 has a capability of breaking ice up to 70 cm thick. It requires a tug to push it and it was found that the operation of a tug with a platform attached is not significantly affected. No specialist ACV skills are required for shipment and assembly of the air cushion ice-breaking platform.

The report recommends further use of air cushion ice-breaking platforms to demonstrate their ability to assist berthing and manoeuvering ships in extended navigation seasons.

**KEYWORDS**

air cushion vehicles

**CLASSIFICATION**

Ice Breaking

ACRES

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Wade, R. G., R. Y. Edwards and J. K. Kim
"Improvements in Ice Breaking by the Use of Air Cushion Vehicles"
The Society of Naval Architecture and Marine Engineering

**NO.**
WA

**SUMMARY**

Observations of ice-breaking operations of air cushion vehicles over the period 1971 to 1974 are described. Limited data from these trials are used to substantiate the hypothesis that ACV's will progress continuously through an ice cover, breaking it up as thoroughly as an icebreaker providing

(a) the vehicle cushion pressure expressed as a head exceeds the ice cover depth

(b) the weight of the vehicle exceeds the weight that would create ultimate collapse of the ice cover.

Model tests were conducted to assess the capability of an ice cushion device deployed at the bow of an ice-breaking ship to decrease the resistance encountered by the ship as the combination proceeds through a field of uniformly thick ice. The tests show that the resistance of the model of a CCGS "Norman MacLeod Rogers" equipped with an air cushion device was reduced by 22 - 42 percent below the resistance which would be encountered without an ACV.

**KEYWORDS**

air cushion vehicles

**CLASSIFICATION**

Ice Breaking

# TRANSPORTATION DEVELOPMENT CENTRE
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# REFERENCE SUMMARY

**SOURCE**

Webb, M. S.
"An Assessment of the Effect of the Niagara Ice Boom on Ice Conditions in Eastern Lake Erie"
Environment Canada, Atmospheric Environment Service
August 1973

**NO.**

WE 73

**SUMMARY**

An assessment was made of the ways in which the Niagara Ice Boom could affect the ice regime of Lake Erie. Although a definitive evaluation was not possible due to a shortage of pertinent data, it would appear that the most significant effect as far as navigation is concerned occurs during the spring breakup. It was estimated that ice retained on Lake Erie by the presence of the boom could extend the ice season by about a day.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

## TRANSPORTATION DEVELOPMENT CENTRE
## ICE CONTROL-ARCTIC PORTS AND HARBOURS
## REFERENCE SUMMARY

**SOURCE**

Webb, W. E. and W. F. Blair
"Ice Problems in Locks and Canals on the St. Lawrence River"
IAHR, 3rd International Symposium on Ice Problems
Hanover, New Hampshire
August 18 - 21, 1975

**NO.**

WE 75

**SUMMARY**

This paper describes the ice control techniques used to alleviate icing problems in locks and canals on the St. Lawrence River.

Remedial works included construction of an ice diversion channel, installation of ice flushing culverts and compressed air systems, and using a polyurethane insulation on lower gates of the locks in combination with electric heating cables along girders. The electric heating cable proved unreliable with high maintenance costs and will be replaced by a hydronic heating system. Timber gate recess bumpers were replaced with steel I-beams with attached electric heating cables.

Cost estimates for various ice control strategies are provided.

**KEYWORDS**

air bubblers, insulation, structures

**CLASSIFICATION**

Ice Diversion
Ice Suppression

TRANSPORTATION DEVELOPMENT CENTRE
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REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Westphal, K. O.<br>"On the Melting of Ice Sheets Under the Influence of a Bubbler System"<br>Bedford Institute of Oceanography<br>Dartmouth, Nova Scotia<br>August 1964 | WE 64 |

**SUMMARY**

The incentive for this study of heat conduction through ice was a result of an expedition under the direction of Dr. E. L. Lewis to Cambridge Bay, NWT.

The author attempts to predict the effect of a bubbler system on a layer of ice given a certain input of heat at the ice-water interface and a boundary condition at the air-ice interface.

| KEYWORDS | CLASSIFICATION |
|---|---|
| air bubblers | Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Williams, G. P.
"Thermal Regime of Lakes and Rivers with Reference to Air Bubbling Systems"
Proc. of the Symposium on Air Bubbling
Ottawa
1961

**NO.**

WI 61

**SUMMARY**

Air bubbling systems have been used successfully to melt ice or prevent its formation in lakes, rivers and ocean areas, but there are cases where they have been unsuccessful. If the action of a bubbler results in the melting of ice or the prevention of its formation, the bubbler must have brought, to the surface, water containing sufficient heat for this purpose. If the water does not contain the required heat it is unlikely that a bubbler will open a hole in an already established ice cover. These facts indicate that before a bubbler system is installed careful consideration should be given to the heat reserves available at a proposed site, and the heat losses to be expected, particularly in those cases where the temperature of the water is just at or slightly above the freezing point. The purpose of this paper is to discuss these thermal factors.

**KEYWORDS**

air bubblers

**CLASSIFICATION**

Ice
Suppression

TRANSPORTATION DEVELOPMENT CENTRE
ICE CONTROL-ARCTIC PORTS AND HARBOURS
REFERENCE SUMMARY

**SOURCE**

Williams, G. P.
"Ice Dusting Experiments to Increase the Rate of Melting of Ice"
Technical Paper No. 239
Division of Building Research, NRC
Ottawa
1967

**NO.**

WI 67

**SUMMARY**

This report evaluates ice dusting based on past published information. The author emphasizes the "near perfect" conditions that are necessary for successful dusting including the minimum daily temperature which should not fall below 0°C irrespective of latitudes as well as zero snowfall during the melting period. The report describes the deterioration of ice for different dusting materials and initial ice thickness.

**KEYWORDS**

ice dusting

**CLASSIFICATION**

Ice
Suppression

| SOURCE | NO. |
|---|---|
| Williams, G. P.<br>"Break-up and Control of River Ice"<br>IAHR Symposium - Ice and Its Action on Hydraulic Structures<br>Reykjavik, Iceland<br>1970 | WI 70 |

**SUMMARY**

This review paper presents background information on the process of river breakup and control of ice during breakup. The limitations and main problems associated with various control methods are summarized.

In particular, control by ice dusting, thermal discharge, explosives, icebreakers, and ice booms is discussed.

| KEYWORDS | CLASSIFICATION |
|---|---|
| ice dusting, thermal discharges, explosives, icebreakers, ice booms | Ice Breaking<br>Ice Diversion, Ice Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
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REFERENCE SUMMARY

| | |
|---|---|
| **SOURCE**<br>Williams, G. P. and L. W. Gold<br>"The Use of Dust to Advance the Breakup of Ice on Lakes and Rivers"<br>Proc. Eastern Snow Conference<br>pp 31 - 56<br>Quebec City<br>1963 | **NO.**<br>WI 63 |

**SUMMARY**

This paper summarizes the findings of several researchers on the subject of ice dusting. Initially described are the influencing factors causing the breakup of ice covers. Importance is attached to the effect of the magnitude and duration of radiation on the melting processes of ice covers. The average air temperatures for southern and northern Canada for which dusting should be feasible are estimated.

The density and particle size of dusting material is considered.

| | |
|---|---|
| **KEYWORDS**<br>ice dusting | **CLASSIFICATION**<br>Ice<br>Suppression |

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**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Williams, W. G.
"Development and Use of Plastic Foam Insulation to Prevent Frost Action Damage to Transportation Facilities"
Proc. Symposium on Cold Regions Engineering
University of Alaska
pp 227 - 276
1971

**NO.**

WI 71

**SUMMARY**

This paper updates developments in the use of plastic foam insulation for highway application and relates experience with other insulated transportation facilities such as airfields and railroads.

Experience with extruded polystyrene insulation demonstrates the basic technical feasibility of the concept and capability of the insulation material.

A description of testing and evaluation of various types of foam plastic insulation is also presented in the reference text accompanying the paper.

**KEYWORDS**

insulation

**CLASSIFICATION**

Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
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# REFERENCE SUMMARY

**SOURCE**

Wortley, C. A.
"Design of Harbor Structures for Boats"
International Conference on Port and Ocean
Engineering Under Arctic Conditions
pp 1,283 - 1,300
1979

**NO.**

WO 79

**SUMMARY**

Design recommendations for fixed and floating boat harbour structures in northern climates are presented. These recommendations include estimates of stationary and moving horizontal and vertical ice forces on boat harbour structures. Additionally, methods to proportion and position structures, and methods to suppress and melt ice are recommended. These methods minimize or eliminate the adverse effects of ice. Information, obtained from extended winter observations in 200 northern harbours, on ice thicknesses, water temperatures, ice cracking patterns, ice collars on pilings, rubble ice accumulations, and damages is also given.

**KEYWORDS**

harbour design

**CLASSIFICATION**

Harbour Ice
Ice
Suppression

# TRANSPORTATION DEVELOPMENT CENTRE
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# REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Wortley, C. Allen<br>"Ice Engineering Guide for Design and Construction of Small Craft Harbours"<br>University of Wisconsin<br>1978 | WO 78 |

**SUMMARY**

This ice engineering guide has been prepared as an aid to designers and builders of small craft harbours in northern climates. It is applicable to lake ice in protected harbours and provides information on the behaviour and properties of ice and ice covers. Other data include

-descriptions of ice pressures of thermal origin and estimated thrusts on structures

-an explanation of the operation and design of compressed air suppression systems

-estimates of safe bearing loads on ice sheets

-estimates of ice up-lift loads.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design, air bubblers | Harbour Ice<br>Ice<br>Suppression |

TRANSPORTATION DEVELOPMENT CENTRE
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REFERENCE SUMMARY

| SOURCE | NO. |
|---|---|
| Wortley, C. Allen<br>"Design of Small-Craft Harbours for Ice Conditions"<br>Prepared for NOAA<br>Rockville, Maryland<br>September 1979 | WO 79 |

**SUMMARY**

Great Lakes small-craft harbour structures are damaged by ice. Information obtained from extended winter observations in 200 harbours is presented. This information, together with design experiences, field tests, laboratory tests, and literature reviews, are used to prepare design recommendations for northern harbours.

| KEYWORDS | CLASSIFICATION |
|---|---|
| harbour design | Harbour Ice<br>Ice<br>Suppression |

**TRANSPORTATION DEVELOPMENT CENTRE**
**ICE CONTROL-ARCTIC PORTS AND HARBOURS**
**REFERENCE SUMMARY**

**SOURCE**

Yee, P., T. E. Wigle and A. Hollmer
"The Lake Erie - Niagara River Ice Boom--An Operational Experience"
IAHR - International Symposium on Ice
Quebec City
July 1981

**NO.**

YE 81

**SUMMARY**

The Lake Erie - Niagara River Ice Boom is installed each winter near the outlet of Lake Erie. Since the boom's inception in the winter of 1964/65, it has reduced the frequency and duration of ice runs from the lake into the Niagara River. Heavy ice runs in the past have caused significant reduction in hydroelectric power production at Niagara Falls, and have caused damages to shore structures along the river. The purpose of this paper is to describe the background and purpose of the boom, its benefits, and recent studies of its possible effects on the local environment.

The ice boom is installed by the power entities with the approval of the International Joint Commission, a bilateral body set up by Canada and the United States to deal with boundary water issues. More emphasis has been placed, particularly in recent years, on the timing of its removal. If dismantled too early, the potential for serious ice runs in the river is increased. On the other hand, some local residents perceive a late removal as lengthening the ice season and prolonging cold weather in the area. Recent studies have shown that past operations of the boom have provided a valuable contribution to the efficient operation of the hydroelectric facilities at Niagara Falls. The boom has reduced riparian damages on the Niagara River and has caused no measurable adverse impact on the local environment.

**KEYWORDS**

ice booms

**CLASSIFICATION**

Ice
Diversion

## TRANSPORTATION DEVELOPMENT CENTRE
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## REFERENCE SUMMARY

**SOURCE**

Zotikov, I. A. and G. P. Moiseeva
"A Theoretical Study of Ice Surface Dusting
Influence on Melting Intensity"
Proc. of Banff Symposium - The Role of Ice and
Snow in Hydrology
Banff
1972

**NO.**

ZO 72

**SUMMARY**

Dusting of ice surfaces is considered to change the intensity of melting mainly because of the change in albedo, due to the dust within a melting layer. A simple model of heat exchange mechanism within a melting layer simplified as a muddy medium where single particles of the dust exchange heat through their whole surface was constructed to calculate the influence of dusting. It was also supposed that, when the number of the particles is great enough, the particles shadow each other and only some of their surface takes part in radiation exchange. To calculate the effect of the shadowing, the probability of the interference is estimated when circles representing the particles are placed independently and randomly on the surface. Formulae were obtained to calculate the change of albedo and intensity of surface melting due to dusting. The comparison of the theory and the experiments showed a sufficient agreement in the results obtained.

**KEYWORDS**

ice dusting

**CLASSIFICATION**

Ice
Suppression